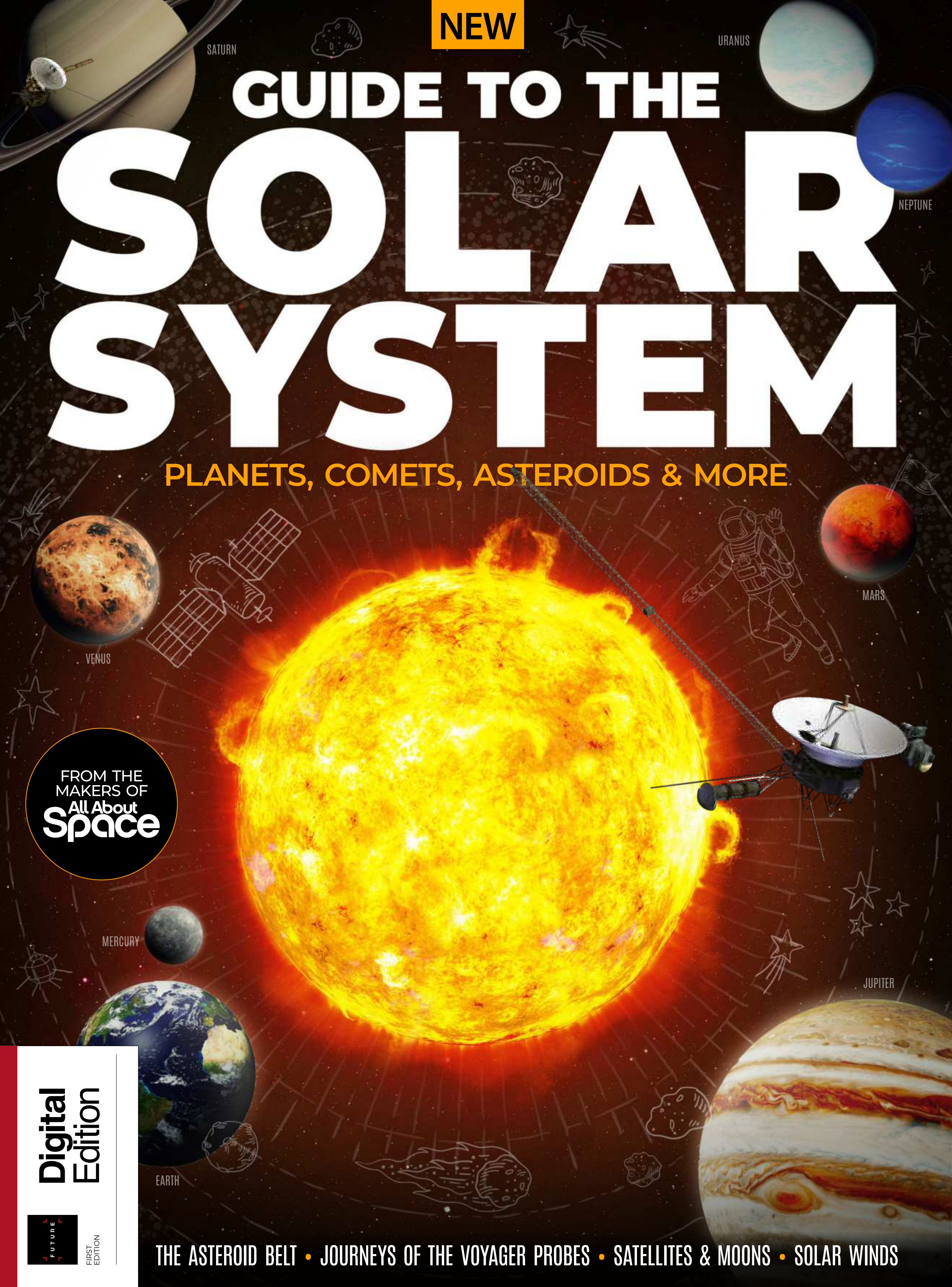
NEW

GUIDE TO THE SOLAR SYSTEM

PLANETS, COMETS, ASTEROIDS & MORE



FROM THE MAKERS OF All About Space

Digital Edition

FUTURE

FIRST EDITION

THE ASTEROID BELT • JOURNEYS OF THE VOYAGER PROBES • SATELLITES & MOONS • SOLAR WINDS

Welcome to the

All About Space Guide to the Solar System

Our Solar System is one of the most interesting places in the galaxy – perhaps in the entire universe. It's the only place we know of so far that harbours life, on one small blue-green planet in the habitable zone of its star. But our planetary neighbours are interesting in their own right too. In this complete guide to our circumstellar neighbourhood, you'll discover everything you need to know about them, from the warm rocky world of Mercury to the distant orbit of the object scientists call Farfarout. You'll discover a wealth of worlds – not just the main eight planets but some of the moons that orbit them, and the dwarf planets that swing through the outer reaches of transneptunian space. The planets and moons of our Solar System will be some of the first places humans will explore when we finally venture beyond our own Earth and Moon. Isn't it time you got to know them?

FUTURE

All About Space

GUIDE TO THE SOLAR SYSTEM

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"EVIDENCE SUGGESTS THE SOLAR SYSTEM BEGAN TO FORM ABOUT 4.57 BILLION YEARS AGO" P10

EVERYTHING YOU NEED TO KNOW ABOUT...

THE SOLAR SYSTEM

Join us on a tour through our current understanding of the planetary system we call home

Reported by Giles Sparrow

INTRODUCING THE SOLAR SYSTEM

Our Solar System consists of the area influenced by the Sun and, apart from occasional stray visitors from interstellar space, everything it contains. Aside from the Sun, its main components are the eight major planets, their moons and rings, a handful of worlds classified as dwarf planets and vast numbers of smaller bodies made of varying amounts of rock and ice, which are broadly termed asteroids and comets. Most of these objects orbit in a plane roughly in line with the Sun's equator and in the same direction as the Sun's rotation – anticlockwise when viewed from 'above' the plane.

The four innermost planets are mostly composed of dense rock and metal. Earth is the largest of these 'terrestrial' planets, with Venus almost the same size, Mars significantly smaller and Mercury the smallest of all. A large gap separates the orbit of Mars from that of Jupiter, the innermost gas giant and the largest planet in the entire Solar System, with a diameter of 11.2 Earths. Saturn is somewhat smaller, and outer Uranus and Neptune are near twins, both about four times the diameter of Earth.

The entire Solar System sits in the Milky Way – a vast spiral galaxy within which the Sun is just one of several hundred billion stars. At about 26,000 light years from the centre, it takes some 230 million years to complete one trip around the galaxy.

AR SCAN HERE

AN EVOLVING SYSTEM

Our neighbourhood hasn't always been quiet

Although today's Solar System seems stable, it represents just a snapshot in a long history of change and evolution. Asteroids and comets in planet-crossing orbits are doomed to suffer disruption of some kind on astronomical timescales, and so their supplies must continuously be replenished. In the first billion years of Solar System history, however, changes were far more dramatic. It's increasingly clear that the giant planets formed closer to the Sun – and to each other – than they are now, and a subsequent gravitational tug of war saw their orbits evolve and change. Jupiter may have first migrated even closer to the Sun, scattering vast numbers of icy objects from the outer edge of today's asteroid belt and beyond into extreme elliptical orbits to form the Oort Cloud, before reversing its track. Neptune may have started its life closer to the Sun than Uranus before their own complex gravitational dance swapped them over, pulling Uranus' axis of rotation over to its extreme 98-degree angle. Some computer models even suggest that in order to reach the current configuration of giant planets, there must once have been a fifth Neptune-sized world that was long ago ejected from the Solar System entirely, or perhaps flung into exile amid the comets of the Oort Cloud.

Below (top): Everything in the Solar System formed from a protoplanetary disc around the Sun

Below: The Sun sends out ionised particles that carry through to the outer reaches of the Solar System

ORIGINS

Evidence from rock grains in ancient asteroids suggests the Solar System began to form about 4.57 billion years ago. Like other stars, the Sun was born from a collapsing cloud, or nebula, rich in gas and dust. As the centre of the cloud grew hotter and denser it began to spin more rapidly, while material around it flattened out into a rotating disc. Dust grains collided and stuck together in the disc, perhaps growing step by step through chance collisions until they had sufficient gravity to draw in more material from around them, or perhaps forming huge clouds of orbiting 'pebbles' that underwent sudden collapse into larger protoplanets when they became unstable.

Meanwhile, as the Sun became hot enough to shine properly, rising temperatures caused easily melted chemicals to evaporate as far out as an 'ice line' in the present-day asteroid belt. Simultaneously, fiery radiation from the newborn Sun and a solar wind of ionised particles blowing out from its surface began to drive gas outwards. While the worlds of the inner Solar System had to form mostly from dry, rocky materials, those farther out incorporated substantial amounts of ice, and in the case of the largest planets were also able to keep hold of huge gaseous atmospheres thanks to their powerful gravity.

THE SUN

Our local star controls conditions across the wider Solar System. With a visible diameter of 1.39 million kilometres (860,000 miles), it accounts for some 99.8 per cent of the Solar System's entire mass and has a composition dominated by hydrogen – the lightest and simplest gas in the universe.

The Sun shines by nuclear fusion, a process that forces hydrogen nuclei together in the core to form nuclei of helium, the next lightest element. Energy is released in the process as photons of high-energy radiation that gradually force their way outwards through the overlying layers, losing energy as they do, and keeping the Sun's interior hot. The Sun's incandescent visible surface, or photosphere, marks the region where its gas becomes cool and sparse enough to be transparent, and visible, infrared and ultraviolet light can escape. This surface has an average temperature of around 5,500 degrees Celsius (9,932 degrees Fahrenheit), although dark sunspots, created where the Sun's tangled magnetic field bursts from its surface, can be a couple of thousand degrees cooler.

Above the photosphere, the Sun's upper layers are home to violent activity that varies, along with sunspot numbers, in an 11-year cycle. The cycle significantly affects the shape of the Sun's corona,

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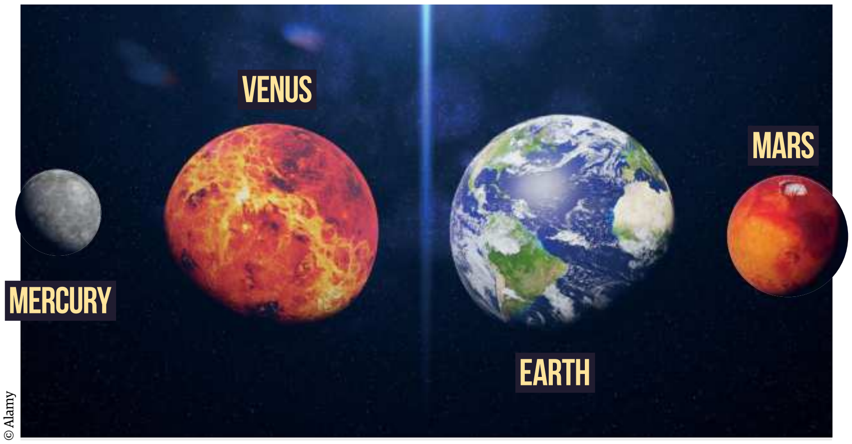
"AS THE SUN BECAME HOT ENOUGH TO SHINE PROPERLY, RISING TEMPERATURES CAUSED EASILY MELTED CHEMICALS TO EVAPORATE"



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Left: Our home planet is the largest of the four rocky bodies closest to the Sun

or outer atmosphere, which typically extends to several times its visible diameter before merging with the solar wind of particles blowing out across the Solar System.

ROCKY PLANETS

A variety of factors have shaped the evolution of the terrestrial planets – most importantly their size, composition and distance from the Sun. As a rule, the larger a planet is, the hotter its interior will remain, giving rise to a more complex structure and potentially a molten metallic core. Size and mass determine a planet's gravity, which along with its temperature and the presence of a protective magnetic field influence how well it can hold on to an atmosphere. These factors influence the chemicals that can exist on its surface.

It's likely that all four rocky planets were bombarded by icy objects from farther out in the Solar System during or shortly after their formation, returning water to their surfaces. Venus, Earth and Mars all once had oceans of liquid water, but Venus' was lost to a runaway greenhouse effect early in its history, leaving behind an arid, hellish landscape. The weak gravity and lack of a protective magnetic field around Mars, meanwhile, allowed much of its atmosphere and water to escape into space, cooling the surface until most of the remaining water became locked in permafrost and the polar ice caps. Venus and Mars show signs of geological activity in the relatively recent past, but this mostly takes the form of volcanism, while activity on Earth is far more complex and continuous.

GIANTS OF GAS AND ICE

The giant planets of the outer Solar System are broadly divided into two pairs: the inner gas giants Jupiter and Saturn, dominated by huge envelopes of hydrogen, and the outer ice giants Uranus and Neptune, made of more complex chemicals such as water, methane and ammonia. All four have deep outer atmospheres that are home to complex weather systems. Despite their size these planets spin rapidly, generating high winds that wrap cloud systems into bands parallel to their equator.

Beneath the active atmospheres of Jupiter and Saturn, pressure from above forces hydrogen into a liquid state, and can even break it down into liquid metallic form, generating extremely powerful magnetic fields. The deeper layers of Uranus and Neptune, meanwhile, are composed of icy chemicals in liquid form. Slow contractions of the inner layers due to gravity, coupled with chemical reactions, generates significant heat inside three of the giants, though Uranus is a mysterious exception, helping to power their weather systems even in the cold outer Solar System.

The considerable gravity of the giants puts each one at the centre of its own substantial satellite system – all four are orbited by a mix of 'regular' moons, formed from material left in orbit as the planet itself formed, and 'irregular' objects captured during later close encounters. Each giant also has a ring system of its own, made up of particles trapped in concentric orbits. These vary wildly between the broad, icy planes of Saturn to the tenuous dust around Jupiter and the tightly defined arcs around Uranus and Neptune.

Source: Wikipedia Commons © Justin Cowart

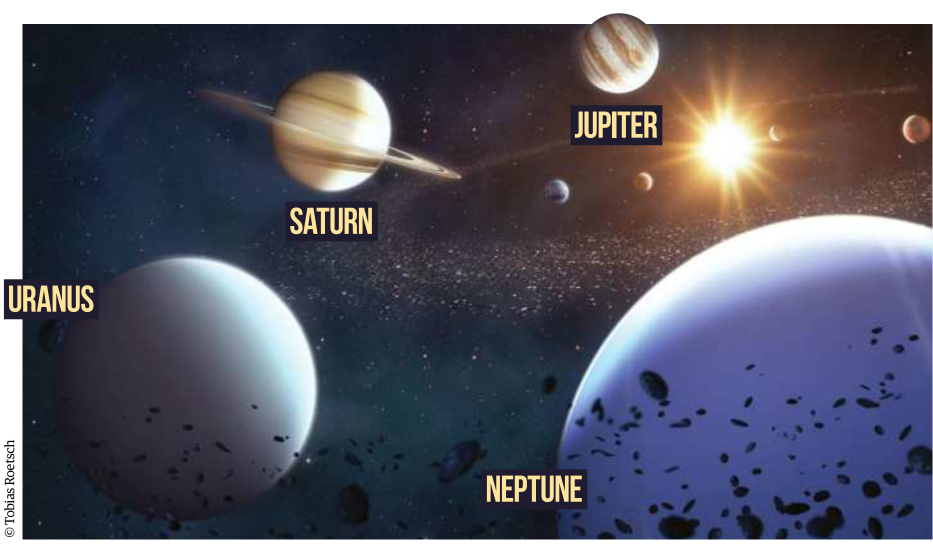
DWARF PLANETS

The term dwarf planet was introduced to clarify the organisation of the Solar System in 2006 – though some might say it's made matters more confusing. Dwarf planets are worlds in orbit around the Sun with sufficient gravity to pull themselves into a spherical shape, but not enough to deflect the paths of other nearby bodies and 'clear their orbits'.

The first dwarfs to be discovered were Ceres in 1801 and Pluto in 1930. Both were originally treated as new major planets, despite their small size, but Ceres was swiftly reclassified as an asteroid once more of its neighbours in the main asteroid belt were discovered. Pluto's status became doubtful in the 1990s as more small bodies in similar orbits were found in the Kuiper Belt, but matters came to a head with the discovery of Eris, another 'trans-Neptunian object' of similar size, in 2003.

Faced with a potentially ballooning list of 'major' planets, astronomers opted to introduce the new category, demoting Pluto, but sweeping up Ceres into the bargain. Because dwarf planets are classified in part by their shape, and this is still uncertain for some distant worlds, there are still fierce debates about which objects qualify. The International Astronomical Union currently recognises just five: Ceres, Pluto, Haumea, Makemake and Eris.

Right: Beyond the asteroid belt, the planets are gaseous and gigantic in comparison to Earth



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LIFE IN THE SOLAR SYSTEM

Could there be life outside of Earth?

Earth's abundant life is due to its unique position in the Solar System near the inner edge of our Solar System's 'Goldilocks zone', where temperatures are neither too hot nor too cold, but 'just right' for liquid water to survive on a planet's surface. Water is widely seen as a key requirement for life because it's the most abundant and effective 'solvent' that we know of – a chemical within which other molecules can dissolve and move around, permitting the encounters and reactions that are needed for life to evolve and survive.

Mars is the only other planet technically just within the Goldilocks zone, and its warmer, wetter history makes it an intriguing destination in the search for past or present life, but there are also surprising possibilities farther from the Sun.

Several large satellites and dwarf planets seem to have liquid-water layers deep in their interiors, while tidal forces raised by Jupiter and Saturn on their icy moons Europa and Enceladus pummel and heat their interiors so much that they have substantial liquid-water oceans just below the surface. Fed with chemical nutrients by undersea volcanoes, these two worlds are seen as the Solar System's most likely spots for alien life to exist.

Right: There are millions of tiny icy and rocky fragments floating through space

Below: 'Oumuamua was identified as an interstellar interloper passing through our Solar System

ROCKY DEBRIS

Although the formation of the Solar System left plenty of rock and dust scattered across the inner Solar System, most of the smaller rocky objects that survive today are confined to the asteroid belt between Mars and Jupiter, where the giant planet's gravity and early shifts in its orbit disrupted any potential for the formation of a fifth rocky planet. Today's asteroid belt contains around 1.5 million asteroids more than one kilometre (0.6 miles) across, along with countless smaller objects.

Although they're scattered across such a vast volume of space that crossing the belt is easy, collisions and close encounters are inevitable on a longer timescale. These lead to the formation of asteroid families with similar compositions and orbits that can be traced back to a common origin. Asteroids vary in composition from 'carbonaceous' objects that have barely altered since the birth of the Solar System to bodies rich in silicate minerals or even iron – fragments of larger ancient worlds that had begun to develop an internal structure before they were smashed apart.

Collisions can also send asteroids onto elliptical orbits that cross over those of the inner planets, with some becoming potentially hazardous near-Earth objects, or NEOs. However, NEO orbits are inevitably unstable over long timescales – ending either in a collision with a major planet or more likely deflection from a close encounter – and so this supply must be steadily renewed.

© Alamy

ICY WANDERERS

The farther out we look in the Solar System, the more volatile ices – not just water ice, but also frozen methane and other compounds – become mixed with the rocky components of solid bodies. This trend is already apparent fairly close to the Sun in the asteroid belt, but it becomes more pronounced among the moons of the giant planets, and above all in the small worlds of the Kuiper Belt beyond Neptune.

The most familiar icy objects, however, are comets. These icy wanderers spend most of their lives in a deep-frozen state, orbiting among the Kuiper Belt objects or even farther out in the Oort Cloud – a vast, spherical comet cloud that surrounds the Solar System. However, they spark into life when chance puts them on an elliptical orbit that brings them close to the Sun. As the comet's solid nucleus warms up, gases evaporating from the surface first form a vast, diffuse atmosphere, called a 'coma', and then an elongated tail that is caught up on the solar wind and dragged away from the Sun.

Comets that visit the inner Solar System may follow orbits that vary from just a few years to tens of thousands. However, each successive visit strips away some of their ice until they eventually become dark, dormant and – depending on their orbits – barely distinguishable from asteroids.

"THESE ICY WANDERERS SPEND MOST OF THEIR LIVES IN A DEEP-FROZEN STATE"

© ESO

TESTING THE LIMITS

Many astronomers from across the world define the Solar System's outer limit as the boundary where the Sun ceases to be the exclusive dominant influence over nearby objects. According to this definition, the edge of the Solar System lies at the heliopause – the wall where the solar wind streaming out from the Sun comes to a halt in the face of pressure from countless other stellar winds and the 'interstellar medium' – clouds of sparse gas that lie between the stars.

This boundary lies around four times farther from the Sun than Neptune, or 120 times farther out than Earth. Four spacecraft – Pioneers 10 and 11 and Voyagers 1 and 2 – have crossed it so far, and the two Voyagers continue to send back data about conditions on the other side.

Despite the widespread adoption of the heliopause as the formal 'edge' of the Solar System, there are many objects in the space beyond it that still orbit the Sun. Most of these lie within either the scattered disc, a broad outer extension of the Kuiper Belt, or the Oort Cloud. According to the most generous definition, the Solar System extends to the edge of the Oort Cloud, roughly a light year from the Sun.

THE EIGHT MAJOR PLANETS

SCAN HERE FOR AR MODELS

MERCURY

Diameter: 4,879 kilometres (3,032 miles)

Mass: 0.055 Earths

Distance from the Sun: 46 to 69.8 million kilometres (28.6 to 43.4 million miles)

Orbital period: 88 days

Rotation period: 58.65 days

Axial tilt: 0.03 degrees

Satellites: Zero

VENUS

Diameter: 12,104 kilometres (7,521 miles)

Mass: 0.815 Earths

Distance from the Sun: 107.5 to 108.9 million kilometres (66.8 to 67.7 million miles)

Orbital period: 224.7 days

Rotation period: 243.02 days

Axial tilt: 177.36 degrees

Satellites: Zero

EARTH

Diameter: 12,742 kilometres (7,918 miles)

Mass: 5.97 billion trillion tonnes

Distance from the Sun: 147.1 to 152.1 million kilometres (91.4 to 94.5 million miles)

Orbital period: 365.256 days

Rotation period: 23 hours and 56 minutes

Axial tilt: 23.44 degrees

Satellites: One

MARS

Diameter: 6,779 kilometres (4,212 miles)

Mass: 0.107 Earths

Distance from the Sun: 206.7 to 249.2 million kilometres (128.4 to 154.8 million miles)

Orbital period: 686.98 days

Rotation period: 24 hours and 37 minutes

Axial tilt: 25.19 degrees

Satellites: Two

JUPITER

Diameter: 139,822 kilometres (86,881 miles)

Mass: 317.8 Earths

Distance from the Sun: 740.5 to 816.6 million kilometres (460 to 506.4 million miles)

Orbital period: 11.86 years

Rotation period: 9 hours and 55 minutes

Axial tilt: 3.13 degrees

Known satellites: 79

SATURN

Diameter: 116,464 kilometres (72,367 miles)

Mass: 95.2 Earths

Distance from the Sun: 1.35 to 1.51 billion kilometres (838 to 938 million miles)

Orbital period: 29.46 years

Rotation period: 10 hours and 34 minutes

Axial tilt: 26.73 degrees

Known satellites: 82

URANUS

Diameter: 50,724 kilometres (31,518 miles)

Mass: 14.5 Earths

Distance from the Sun: 2.74 to 3.01 billion kilometres (1.7 to 1.87 billion miles)

Orbital period: 84.02 years

Rotation period: 17 hours and 14 minutes

Axial tilt: 97.77 degrees

Known satellites: 27

NEPTUNE

Diameter: 49,244 kilometres (30,598 miles)

Mass: 17.1 Earths

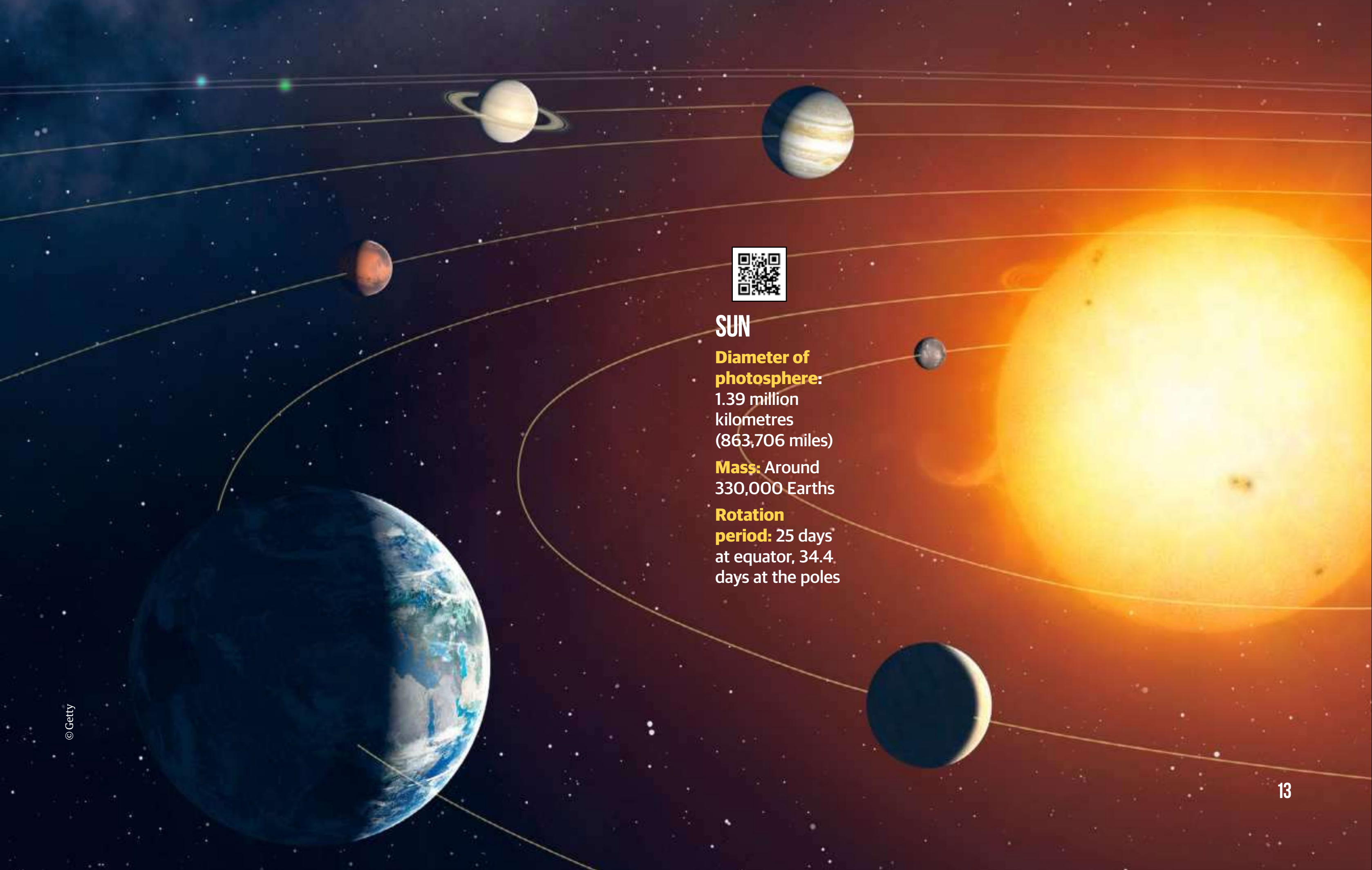
Distance from the Sun: 4.44 to 4.54 billion kilometres (2.76 to 2.82 billion miles)

Orbital period: 164.8 years

Rotation period: 16 hours and 7 minutes

Axial tilt: 28.32 degrees

Known satellites: 14



SUN

Diameter of photosphere: 1.39 million kilometres (863,706 miles)

Mass: Around 330,000 Earths

Rotation period: 25 days at equator, 34.4 days at the poles

WHAT DID OUR SUN LOOK LIKE IN ITS INFANCY?

New findings may shed light on what our star looked like in its youth

Reported by Charles Q. Choi

Newborn stars are surrounded by a disc of gas and dust from which planets, asteroids, comets and moons are born. The star's magnetic field connects the star with this protoplanetary disc, "funnelling material from the disc onto the star," said Catherine Espaillat, an astrophysicist at Boston University. In a recent study, Espaillat and her colleagues investigated the spot where a star's magnetic field deposits protoplanetary disc material onto a star. "This footprint is called the 'hotspot' since the material is very hot when it slams onto the surface of the star," she explained. They focused on GM Aurigae, a star about the same mass as the Sun located about 420 light years away in the constellation of Auriga.

GM Aurigae is only about 2 million years old; in comparison, the Sun is about 4.6 billion years old. Previous work could not get a clear picture of the structure and dynamics of these hotspots. But in the new study, the researchers analysed GM Aurigae with multiple space and ground-based observatories. "This is the first time such an extensive time-coordinated study has been done on a young star," Espaillat said.

The scientists found the visible light they detected from GM Aurigae peaked in brightness about a day after ultraviolet light. They suggested this happened because the source of the visible and ultraviolet light moved into and out of view as it rotated along with the star.

When combined with computer models of matter accreting onto stars, these findings suggest the hotspot varies in density from its centre to its rim on the star's surface. Areas of the hotspot with different densities have different temperatures and so emit different wavelengths of light.

"For the first time, we mapped the structure in this hotspot using observations and confirmed theoretical predictions," Espaillat said. "This result teaches us more about what our Sun looked like when it was young. Now our Sun has sunspots, dark areas where the temperature on the surface is cooler. When our Sun was young, it also had hotspots." Future research will analyse GM Aurigae and other stars to detect more details about these hotspots.

"THIS IS THE FIRST TIME SUCH AN EXTENSIVE TIME-COORDINATED STUDY HAS BEEN DONE ON A YOUNG STAR"
CATHERINE ESPAILLAT

Left: Studying Sun-like stars can tell us more about our stellar host

OUR SUN IS GETTI HOTT

As our nearest star enters its next solar cycle, physicists have revealed what the future holds - and it's not what they expected

Reported by James Romero

© Tobias Roetsch

As a life-giver that warms and lights up our world, it is easy to forget the true, violent nature of the Sun. As the Sun enters a new cycle of surface activity, we are only now beginning to fully appreciate the wide-ranging ways our star's changeable nature can impact our planet and modern lives.

Solar weather describes the influence of the Sun on the Earth-space environment. Back in 2011 it was added to the UK government's National Risk Register and placed on a similar level to the emergence of a new disease due to the number of people it could potentially impact on Earth.

"The Sun is very dynamic," says Helen O'Brien, lead engineer on the European Space Agency's Solar Orbiter mission. "It has different moods, it is very explosive and it has the potential to damage our modern infrastructure." As well as providing heat and light, our star is constantly throwing out more deadly material. The solar wind is the name given to this constant stream of energised, charged particles, primarily electrons and protons.

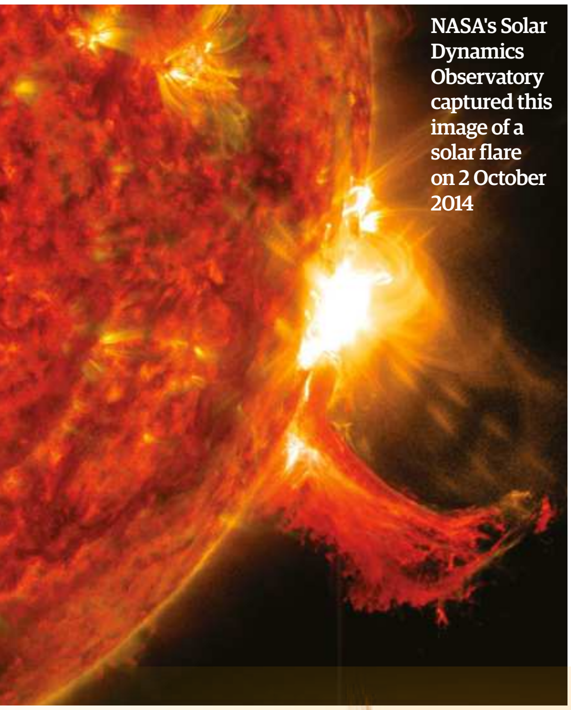
On Earth we are shielded by our planet's magnetic field while high-energy X-rays and ultraviolet light are absorbed high up in the atmosphere. They electrify their surroundings to create the Earth's ionosphere and simultaneously excite constituents of our own atmosphere so they glow and create the famous aurorae.

> "[THE SUN] IS VERY EXPLOSIVE AND HAS THE POTENTIAL TO DAMAGE OUR MODERN INFRASTRUCTURE"
>
> HELEN O'BRIEN

While the aurorae are harmlessly enjoyed by polar communities and tourists, the Sun's own magnetic field can throw far more violent eruptions our way. Its much larger field is composed of a series of magnetic lines that connect distant points on the surface. Over time these lines can become twisted as the Sun's compositional fluidity sees material at its equator rotate faster than at its poles, and the magnetic field gets wrapped around the star. "When you distort a magnetic field it is like stretching an elastic band," says Chris Scott, professor of Space and Atmospheric Physics at the University of Reading. "You are storing up energy."

Those magnetic distortions cause complex knots to form, which burst to the surface as sunspots. When the Sun is very active you have lots of energy stored up in these knots, and occasionally the system will reconfigure itself through solar flares that throw out vast quantities of high-energy plasma like a cloud from the Sun's atmosphere.

These eruptions can be incredibly violent. The largest, known as coronal mass ejections, can contain billions of tonnes of material, which travels out at speeds of several million miles per hour.



NASA's Solar Dynamics Observatory captured this image of a solar flare on 2 October 2014

If Earth is in the crosshair of these large storms the consequences can be both spectacular and costly. This was evident even back in September 1859 on the night of the most famous direct hit, known as the Carrington event, which bathed almost the entire surface of the Earth in beautiful aurorae. Though Carrington was spectacular in its scale and spectacle, it was also the first example of solar weather impacting our technology – recently rolled out telegraph systems in America and Europe were hit by fires and gave people electric shocks.

In today's information age of integrated power networks and satellite communications, a similar strike today could bring down radio communications and upset electronics on the ground, causing long-distance power grids to fail. In 1989 a coronal mass ejection blacked out the entire Canadian province of Quebec, while last year an economic risk assessment by researchers from the University of Oxford found that a Carrington-style event could leave the UK with £15.9 billion (approximately $20.5 billion) worth of damage.

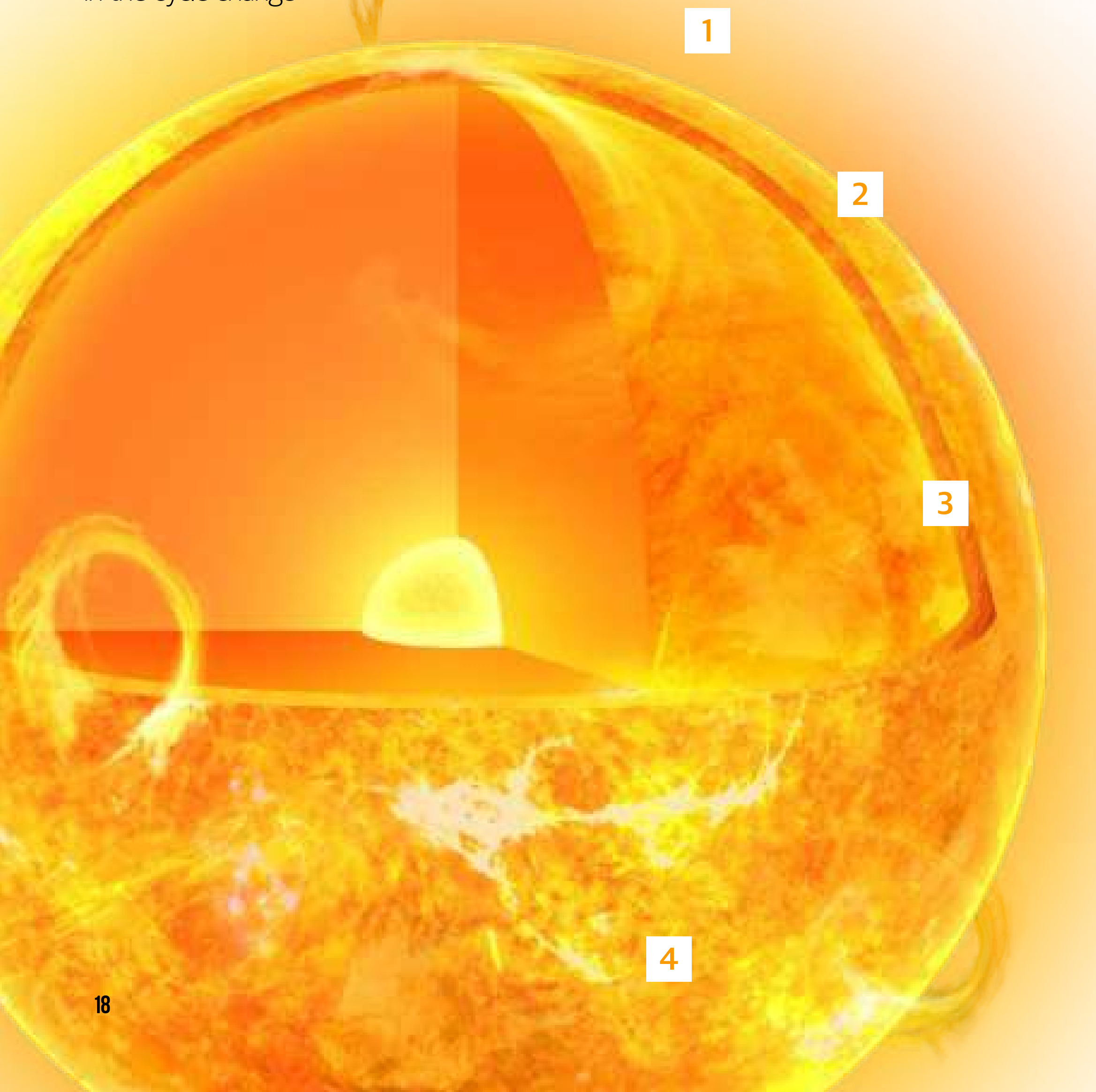
In general, a direct threat to human life on the Earth's surface is low. However, a small proportion of our population are spending more and more time higher up, and that does create risks. Storms increase the radiation impacting spacecraft to levels that could threaten astronaut health, while more transatlantic flights are crossing the poles where solar wind material is constantly funnelled by Earth's magnetic field.

Exposure from a single flight during normal solar conditions will be tiny, but there is concern for flight staff working up there year round. Also, recent research from Clive Dyer of the University of Surrey Space Centre suggests flying in modern aircraft

"A STRIKE TODAY COULD BRING DOWN RADIO COMMUNICATIONS AND UPSET ELECTRONICS ON THE GROUND, CAUSING POWER GRIDS TO FAIL"

WHAT'S GOING TO HAPPEN TO THE SUN?

Each layer of our home star is affected in the cycle change



1 SUN'S MAGNETIC FIELD

The magnetic field transitions from a simple arrangement at solar minimum to a complex tangled web as it wraps around the Sun, though recent cycles haven't produced the same intensity of maximum.

2 CORONA

Though generally marked by lower output, solar minimums can still see heightened periods of high-energy particles released from this upper-atmospheric layer as the Sun's magnetic field creates holes in the corona. However, it's during the solar maximum when the corona will be most active, full of spinning tornados, nanoflares and looped-shaped helmet streamers. As you move towards solar maximum solar flares push more frequently through the corona, heating its gas up.

3 PHOTOSPHERE

On the surface of the lowest layer of the Sun's atmosphere, the start of a new cycle is marked by the appearance of sunspots in higher latitudes. Solar flares also become much more common as you approach solar maximum.

4 CHROMOSPHERE

The second of the Sun's three atmospheric layers experiences frequent heating by ascending solar flares as you approach the solar maximum. Solar prominences, gigantic plumes of gas rising up from the photosphere, are also more abundant at solar maximum and during louder solar cycles. As are spicules, jet eruptions of gas that shoot upwards and outwards into the corona.

SUN'S EFFECT ON THE PLANETS

Whether stripping them away or lighting them up, the atmospheres of the Solar System's worlds are continually shaped by the output of our star

1 VENUS

Without its own magnetic field lighter gases from Venus' thick atmosphere, including water vapour, are continuously blown away by the solar wind, creating an ionosphere that resembles a comet's tail emanating from its night side.

2 MERCURY

Mercury's close proximity to the Sun and lack of atmosphere leaves its relativity weak magnetic field swamped by solar eruptions and its surface bathed in the radiation of the solar wind.

3 MARS

Mars' diminutive size and weak gravitational hold left it unable to cling onto its early thick atmosphere as its own magnetic field was lost when its molten interior cooled and solidified. It was subsequently stripped away over time by the solar wind.

4 JUPITER

Recent data from NASA's Juno spacecraft suggests Jupiter's powerful blue aurorae are not entirely powered by the same solar wind mechanism behind aurorae on the other planets. Can the largest planet in our Solar System generate its own?

5 SATURN

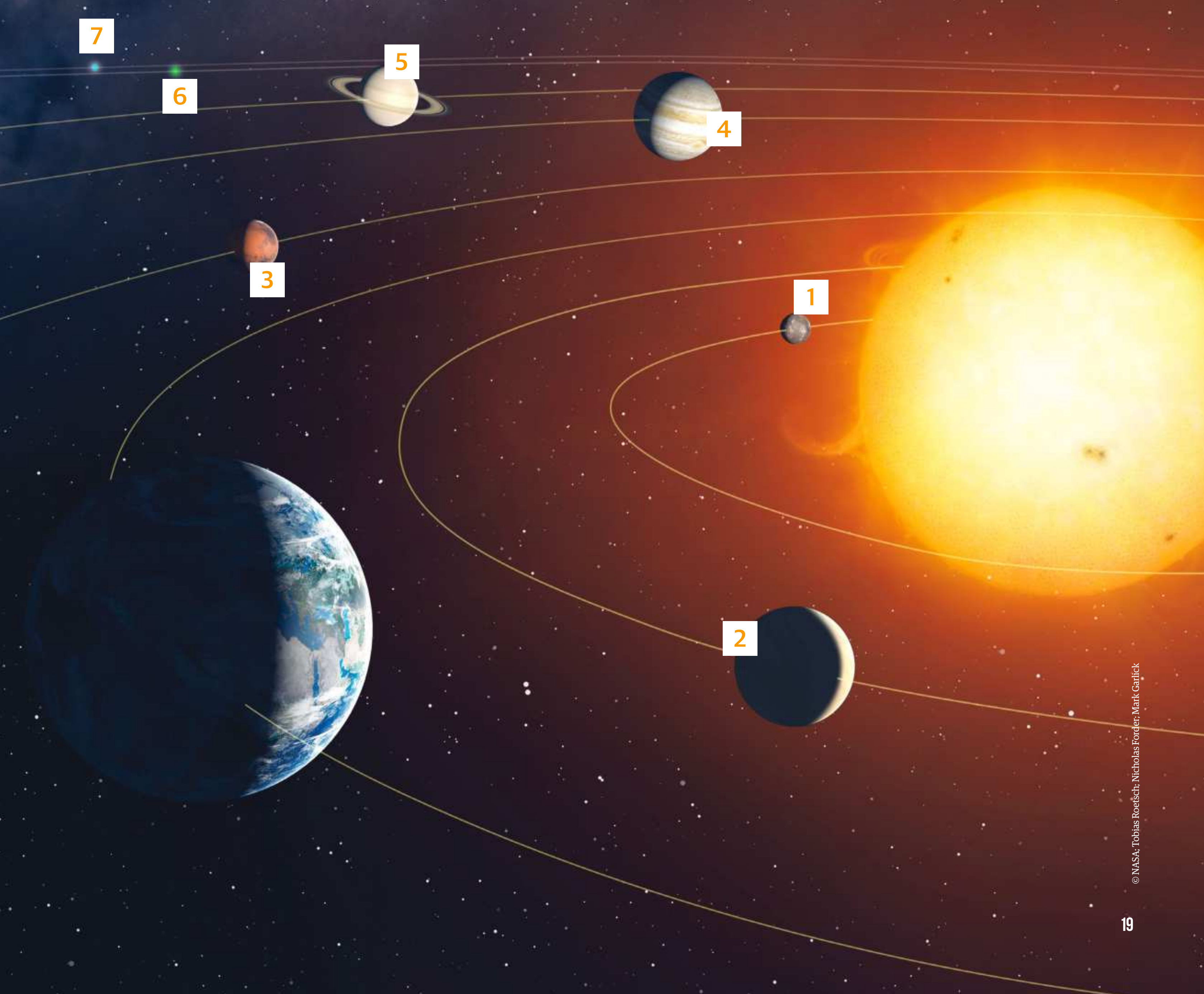
Above and below its ringed equator, Saturn's poles are regularly lit up by strong aurorae, though as they are in the UV and infrared part of the spectrum they would be invisible to us. However, weaker aurorae of pinky-purple visible light have been observed.

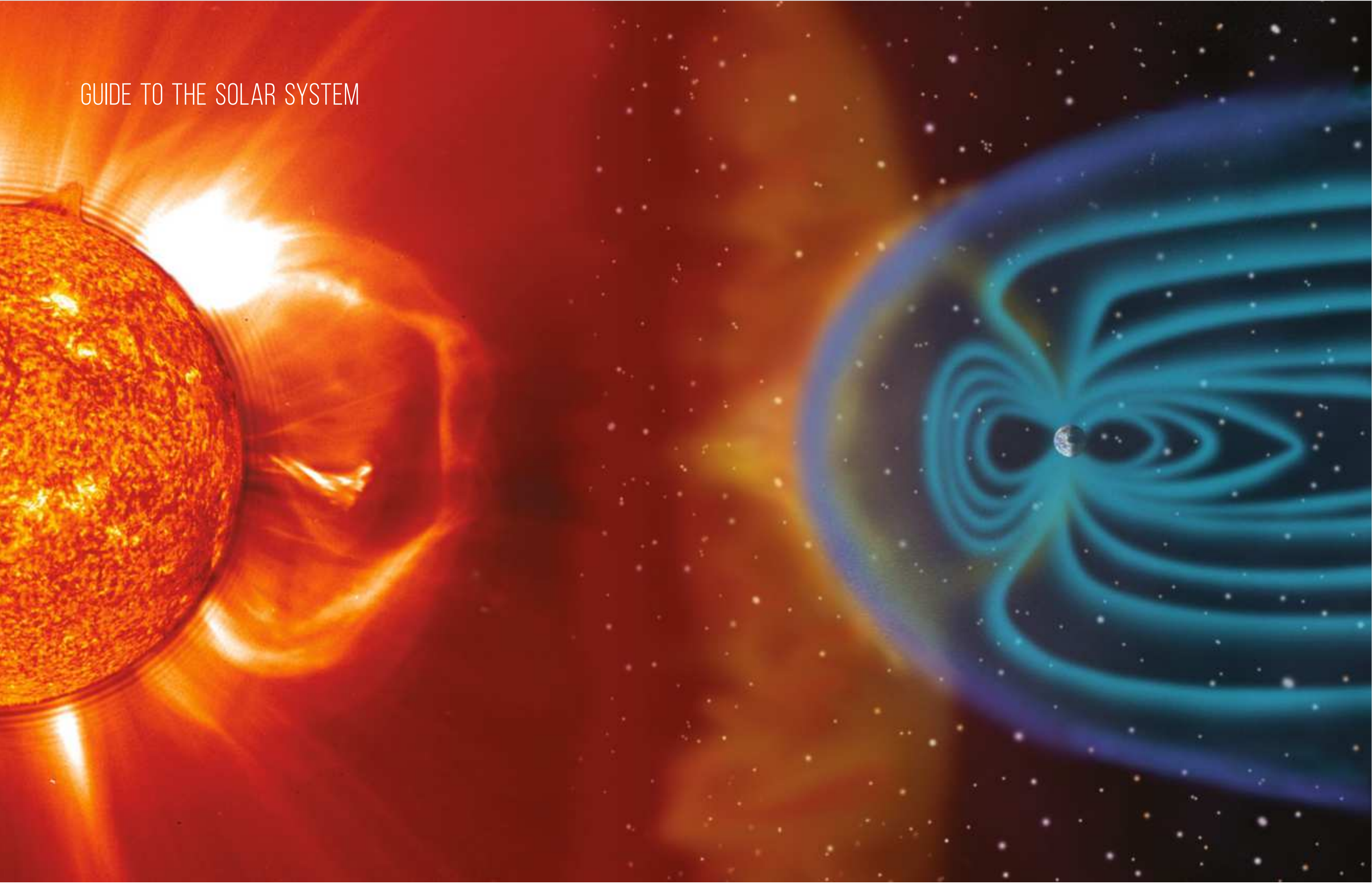
6 URANUS

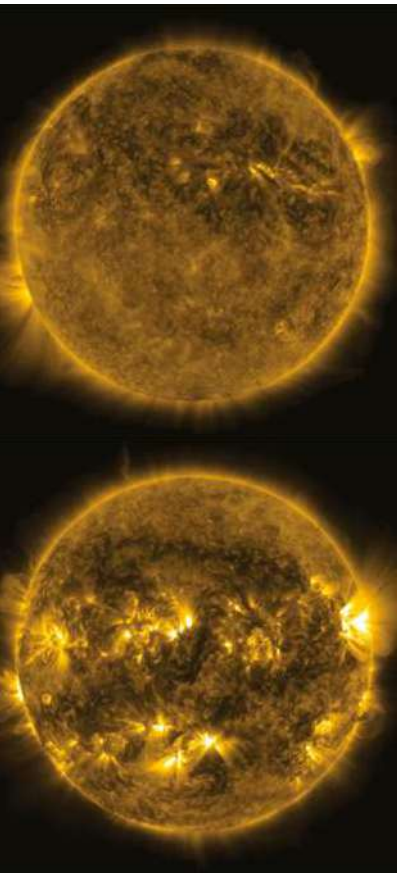
On Uranus the solar wind excites atmospheric hydrogen to create its aurorae, which can be found close to its geographical – though not geomagnetic – equator, as the planet orbits on its side.

7 NEPTUNE

Aurorae were spotted on Neptune by the Voyager 2 flyby in the 1990s. However, the distinct offset between the planet's magnetic field and its rotational axis means these weak light displays can be found across the surface.







during a solar storm could expose passengers to radiation levels equivalent to the annual working limit for air crews. This threat has left satellite companies, aircraft operators and power companies monitoring the solar cycle for clues as to when the threat level will be at its highest.

By counting sunspots on the Sun's surface scientists have for some time known of 11-year cycles of increasing and decreasing solar activity and surface eruptions, driven by the tangling and untangling of the magnetic field lines. These plots indicate we are approaching the latest solar minimum, and therefore entering a new cycle.

Recent magnetic field evolution models developed by the Center of Excellence in Space Sciences in India concluded that the solar maximum of the next cycle, solar cycle 25, will occur around 2024. They also suggested the cycle could buck a wider trend of decreasing solar maximum intensities since the early 1990s, though perhaps not in a way that would greatly threaten ground- or space-based infrastructure.

"It is unlikely that this will affect big solar storms, as these can happen at any stage of the solar cycle," says Scott. However, anticipating the timing and severity of the coming solar cycle could help us prepare for the more local effects such solar variability that effect our lives and which have only come to light in the last decade or two.

Researcher Pablo Mauas has published a series of papers analysing river flows of the Paraná River, as well as measuring snow accumulation and counting tree rings to establish a remarkable agreement between local precipitation rates and the number of sunspots, tracked back over many decades. "I can quite believe there is an 11-year cycle in the flow rates of the river," says Scott, who points to evidence of similar solar-influenced systems closer to home.

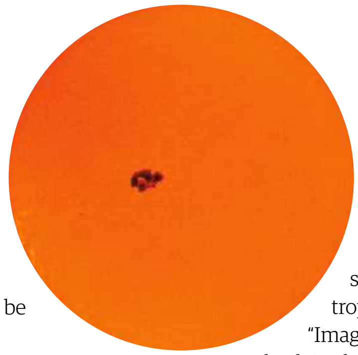
During recent low periods of solar activity it seems the jet streams become more meandering, and you get more 'blocking events' where air-pressure systems get stuck over a certain location. These phenomena are thought to account for some of the very cold recent winters in northwest Europe, but perhaps this trend may reverse slightly if the next solar cycle is more active, as the Indian research team suggests.

In his own research Scott has shown that fast jets of solar wind passing the Earth, associated with more active solar periods, can result in a substantial increase in lightning strikes across Europe for up to 40 days as a result of disturbances to the electrical properties of the atmosphere. While communities and populations may need to adapt to changes in these localised weather systems, a better way of predicting larger scale solar weather on a more detailed day-to-day basis is an urgent priority.

This becomes more pressing if Carrington events prove to be more common than that 'once-in-a-century' tag. Reanalysis of magnetic behaviour measurements in the Earth's atmosphere by Scott's colleague Mike Lockwood has found storms in

Above: A CME blasting from the Sun's surface in the direction of Earth

Left: The Sun goes through a natural solar cycle every 11 years, composed of significant increases and decreases in sunspots and eruptions



1941 and 1972 that may have been as big, if not bigger, than Carrington, but had surprisingly little impact. "It might be that the biggest parts occurred over parts of the world where there wasn't the technological infrastructure to be disturbed," says Scott.

There was also a storm in July 2012 that narrowly missed the Earth and fortunately hit a solar-observation spacecraft from the Solar TErrestrial RElations Observatory (STEREO) mission. It was travelling fast enough that if it had been on target it would have triggered a modern-day Carrington-like event. If we are not to be so fortunate during the next solar cycle we will need to investigate ways to provide more detailed forecasts of what is coming at us.

"It's like on Earth; we can say the winter will be colder than the summer and we will get more rain," says O'Brien. "But what you really want to know is if it is going to rain on the day of your party." However, there are challenges replicating our ability to predict Earth weather in space.

Meteorologists utilise a vast network of monitors collecting data 24/7 as satellites constantly track weather systems from above in order to run their increasingly sophisticated simulations.

And while we have models of the solar wind and how it propagates through space and interacts with the Earth, we can't look down on the entire system as we can when tracking tropical storms or rain fronts. "Imagine yourself as a meteorologist back in the pre-space age in the 1950s, and you are trying to make sense of all these spot measurements without the benefits of a satellite picture. That's probably where we are with space weather," says Scott.

Reliable space weather forecasts will also require a greater understanding of the relationship between what we see on the Sun's surface and what is in line to hit us several hours or days later. To help in this endeavour we have sent up a community of craft to monitor the Sun. However, they are all primarily scientific missions sent up to answer scientific questions. "They are proving useful, but they are not optimal," says Scott, whose STEREO mission can only provide data at the end of each day, which isn't much use when really powerful, fast-moving storms can get to Earth in 17 hours.

The scientific community are in regular contact with industry and space agencies who are working to ensure they have spares at the most

Left: A massive sunspot around the size of Jupiter is identified by the SOHO spacecraft in 2003

Below: Satellite operators have been warned of the dangers a large solar storm could pose

"A LOT OF SATELLITE OPERATORS CHOOSE NOT TO WORRY ABOUT FORECASTS BECAUSE THEY DO NOT HAVE SUFFICIENT ACCURACY" PROFESSOR CHRIS SCOTT

WHAT IF OUR SUN BECAME TOO ACTIVE?

With enough notice and preparedness we could negate the dangers and simply enjoy the greatest light show of all time

ALL EYES TO THE SKIES
If major solar activity were to threaten Earth, our solar science community and their legion of orbiters as well as land-based observatories would need to work out the likelihood, scale and arrival date of a direct hit.

PLANES TAKE THE LONG WAY AROUND
To avoid endangering staff and passengers with exposure to high radiation levels, operators of transatlantic flights would be encouraged to avoid usual 'over the poles' routes.

ASTRONAUTS TAKE REFUGE
During an intense solar storm any planned spacewalks are cancelled and astronauts would be asked to set themselves up in the most shielded modules of the station.

SATELLITES SWITCHED TO SAFE MODE
If given sufficient notice of an incoming solar storm satellite operators would be encouraged to switch any orbiting units to safe mode.

SAVING POWER
To avoid widespread blackouts power companies will need significant stocks of replacement transistors and crew deployed on the ground to tend to damaged parts of their grids

THE GREATEST LIGHT SHOW ON EARTH
One positive effect of intense solar activity is the chance for more people to enjoy the northern and southern lights at much lower latitudes than usual are bathed in aurorae.

SOLAR SURVEYORS
In order to better understand and anticipate solar weather space agencies have sent up a family of orbiters, satellites and probes.

SOLAR SURVEYORS

In order to better understand and anticipate solar weather, space agencies have sent up a family of orbiters and satellites

1 PARKER SOLAR PROBE

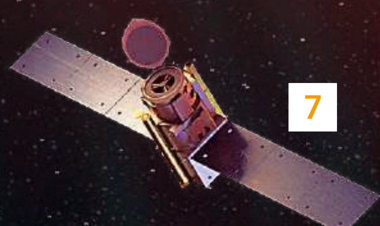
The mission to 'touch' the Sun, this probe is the first man-made object to get within 6 million kilometres (4 million miles) of the Sun's surface. At that distance it measures the pristine solar wind up close before the 'outburst' gets jumbled up in the journey towards Earth.
RESULTS: Pending

2 SOLAR ORBITER

Due to launch in 2020, it combines solar wind particle and magnetic field measurements with direct surface observation. It will monitor the Sun on highly elliptical orbits which will allow it to spend 10 to 15 days co-rotating with the Sun, providing uninterrupted coverage of sunspot, flare and storm development.
RESULTS: Pending

3 ACE

Launched back in 1997 to study the energetic particles from the solar wind, as well as providing the NOAA Space Weather Prediction Center with data for forecasts and warnings of solar storms.
RESULTS: Discovered that the current solar cycle, as measured by sunspots and coronal mass ejections, has been much less magnetically active than the previous cycle.

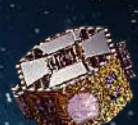


5 WIND

A NASA science spacecraft launched in 1994 to study radio waves and plasma that occur in the solar wind and in the Earth's magnetosphere.
RESULTS: Researchers have found evidence for a type of plasma wave moving faster than theory predicted within the solar wind using Wind data. The research suggests that a different process than expected may be driving the waves.

4 IBEX

A NASA satellite launched in 2008 that aimed to map the boundary between the Solar System and interstellar space.
RESULTS: In 2013, IBEX results revealed the Sun's heliosphere has a tail.



6 IRIS

A NASA satellite launched in 2013 to Investigate the physical conditions at the very edge of the Sun's visible disc – known as the solar limb. In particular it has looked at the chromosphere layer, whose rosy-red colour is only usually visible to us on Earth during eclipses.
RESULTS: IRIS has shown that the interface region of the Sun is significantly more complex than previously thought and includes features described as solar heat bombs, high-speed plasma jets, nano-flares and mini-tornadoes.

7 HINODE

A Japan Aerospace Exploration Agency-led satellite whose Sun-synchronous orbit over the day/night terminator allows near-continuous observation to explore the magnetic fields of the Sun.
RESULTS: In 2018 astronomers using the Hinode spacecraft observed the strongest magnetic field ever directly measured on the surface of the Sun.

8 STEREO

Two near-identical spacecraft launched in 2006 into orbits around the Sun ahead of and behind the orbit of the Earth. This enables stereoscopic imaging to provide in-depth information when observing solar phenomena, such as coronal mass ejections.
RESULTS: One of the STEREO craft – STEREO A – was in the path of the solar storm of 2012 which was similar in strength to the Carrington Event. Its instrumentation was able to collect and relay a significant amount of data about the event.

9 SOHO

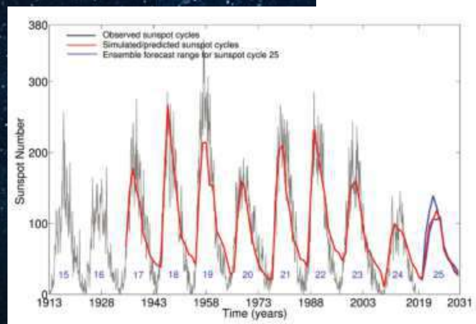
One of the original craft still in operation, SOHO was launched in 1995 and combines imagers and spectrometry instruments to probe the layered structure of the Sun with in-situ measurements of the solar wind as it goes past.
RESULTS: SOHO has also discovered over 3,400 comets as they orbit around the Sun, as well as providing the main source of near-real-time solar data for space weather prediction.

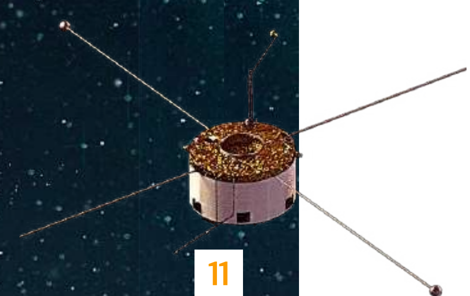
10 SOLAR DYNAMICS OBSERVATORY

Launched in 2010 to investigate how the Sun's magnetic field is generated and structured and how this stored magnetic energy is converted and released into the heliosphere in the form of solar wind, energetic particles and variations in the solar irradiance.
RESULTS: Has identified possible precursors to space weather in the behaviour of plasma within the regions encircling sunspots.

12 DSCOVR

Originally proposed by then-Vice President Al Gore, DSCOVR monitors variable solar wind conditions and their impact on the Earth, including changes in ozone, aerosols, dust and volcanic ash, cloud height, vegetation cover and climate.
RESULTS: Took the second picture of the entire Earth, following on from the final Apollo mission's famous Blue Marble picture.





11 CLUSTER II

Launched in 2000, the Cluster II mission is an in-situ investigation of the interaction between the solar wind and the magnetosphere by using four satellites.
RESULTS: Has developed the first models of the Earth's magnetic field and its interaction with the solar wind based on actual measurements rather than theory.

Above: Researchers have modelled the number of sunspots between 1913 and 2031

Below: The coronal mass ejection, viewed in four extreme ultraviolet wavelengths, in 2012 that sent a massive solar storm that just missed Earth

vulnerable parts of their grids, safe modes for their satellites, back-up routes for transatlantic airlines and safe houses for orbiting astronauts. However, today's rudimentary early warning systems make preparedness a significant economic risk.

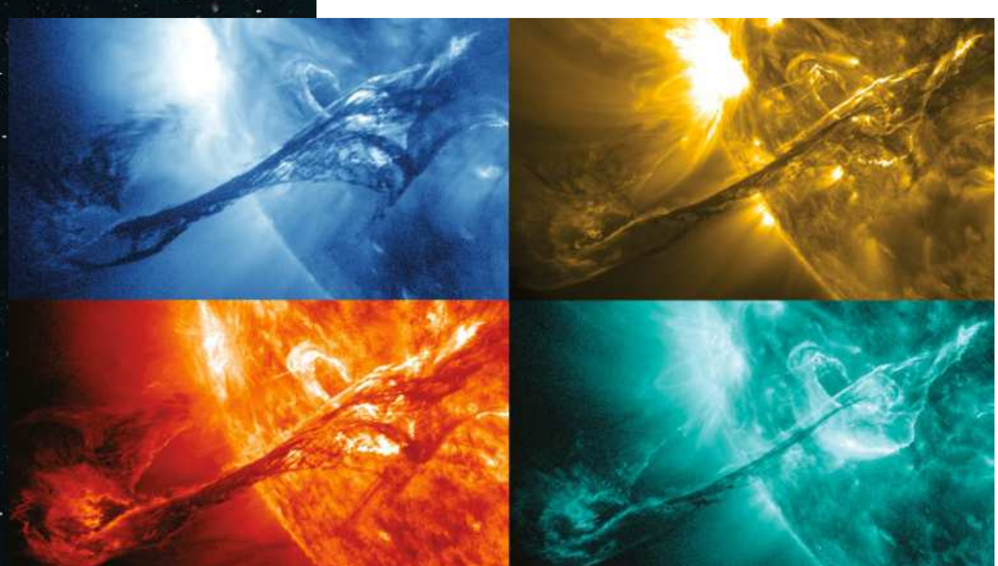
"A lot of satellite operators choose not to worry about space weather forecasts because they do not have sufficient accuracy to make it worth their while," says Scott, who calls for a new observation-focused mission to put a spacecraft out far enough to see the Sun and the Earth in the same field of view. It would be stationed near enough to us to provide continuous real-time observations.

Further notice could be provided by looking for signature surface behaviour that proceeds major eruptions. This is where two of the latest additions to the Sun's community of human-made companions could prove useful. O'Brien's ESA-funded Solar Orbiter mission is due to launch in 2020. It combines solar wind particle and magnetic field measurements with direct surface observation, all from inside the orbit of Mercury.

Key to the Solar Orbiter's ability to spot impending eruptions will be its highly elliptical orbit, which will allow it to spend 10 to 15 days co-rotating with the Sun, providing uninterrupted coverage of sunspot, flare and storm development.

While the Solar Orbiter will take direct solar observation closer than ever before, NASA's Parker Solar Probe is pushing the boundary yet further. On its journey to 'touch' the Sun the probe will eventually fly as close as 6.1 million kilometres (3.8 million miles), meaning it will pass through the Sun's outer atmosphere.

At that distance it hopes to measure the pristine solar wind – what it looks like when it leaves the Sun before it gets jumbled up in the 150-million-kilometre (93-million-mile) journey to Earth. "We will be able to couple together unprecedented details on what is happening on the dynamic, bubbling, boiling surface of the Sun with what is going in interstellar space," says O'Brien, who believes these new data sets and monitoring stations provide hope for our ability to give fair warning of future eruptions during the next solar cycle.



IS OUR SUN GOING INTO HIBERNATION?

Each sunspot cycle has been getting less intense. Is our star falling asleep?

Reported by Kulvinder Singh Chadha

Solar activity refers to the state of the Sun's magnetic field and associated phenomena: sunspots, flares, solar wind and coronal ejections. During periods of minimal solar activity, such events are often uncommon and weak. During solar maximum, they're at their strongest and most frequent. Magnetic field fluctuations on the Sun can happen on drastically different timescales, ranging from seconds all the way to billions of years. When astronomers speak of a 'slow down' or a period of quiescence in the Sun's activity, it doesn't mean the Sun will stop shining, but that there's a slow down in activity.

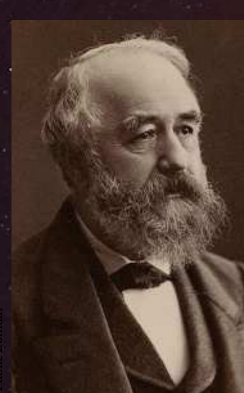
The Sun has one particular rhythm, lasting approximately 11 years, in which its polar magnetic field flips polarity. Sunspots serve as an indicator of this change. Indeed, it's often known as 'the sunspot cycle'.

Although sunspots themselves were first observed by Galileo, Christoph Scheiner and others from 1609 onwards, the cyclical nature of their appearance and disappearance was first noted in 1775 by Danish astronomer Christian Horrebow. It was then rediscovered in 1843 by Heinrich Schwabe. In 1848, Swiss astronomer Rudolf Wolf used Schwabe and others' results, as well as performing his own observations, to calculate the 11-year cycle and a mathematical method to count the number of sunspots. This so-called 'Wolf number' remains in use today.

Many other astronomers at the time either independently observed this cycle or were inspired by the results of others. Wolf's own calculation of the 1755 to 1766 sunspot cycle was labelled as the first, and each sunspot cycle since then has been progressively numbered as such. We are now in Cycle 25.

But sometimes the spots don't appear at all. This was the case for 80 days of the first six months of the current solar cycle, which started in December 2019. It was greater still for the same period in Cycle 24, where there were 139 spot-free days. The period from 1645 to 1715 saw a near-total crash in sunspot numbers, where they could literally be counted on two hands.

Wolf struggled to piece together solar cycles before the mid-1700s because of this dearth of information, but it didn't mean sunspots weren't



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Left: The modern numbering of solar cycles comes from Rudolf Wolf, who studied them back to 1755

© Nicholas Forder

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being observed. Many distinguished astronomers of the age, such as Giovanni Cassini, continued to make observations. This 70-year solar lull was later noted by German astronomer Gustav Spörer, which then later inspired the British-Irish husband and wife team Edward and Annie Maunder. The period has since been named the Maunder minimum. There have been other lulls before and since, such as the Spörer and Dalton minima.

But in 2020 Cycle 25 actually had 80 per cent more sunspots overall than the equivalent period for Cycle 24, suggesting that the current cycle may in fact be stronger, rather than weaker. The international Solar Cycle 25 Prediction Panel said in September 2020 that they expect Cycle 25 to be about as strong as Cycle 24. Has the consensus changed since then, or is it still the same?

"The consensus has not changed," says panel co-chair Dr Doug Biesecker. The consensus is still that the current cycle will be much like Cycle 24. "We have not seen anything that differs significantly in the early stages of this cycle that varies from the panel prediction of a peak of 115 [sunspots] in July 2025." The predictions are based on the 13-month 'smoothed sunspot number' – a statistical method for calculating sunspots. And you have to be patient when studying the Sun. As Biesecker says: "It can take up to three years after the cycle begins before we can say with confidence whether the prediction is still valid."

Successfully predicting solar weather is certainly essential when testing scientific theories about how the Sun works. But there's a more pressing practical reason for doing so. Strong solar flare events and coronal mass ejections – most likely to occur around the time of solar maxima – can disrupt modern technology.

The flux of high-energy particles can damage spacecraft, satellites and even ground-based power systems. The latter are particularly vulnerable, as solar radiation easily disturbs Earth's magnetic field, inducing currents in long power lines. Such a geomagnetic storm destroyed large grid transformers and shut down the whole of Quebec, Canada, in March 1989. And this was just history repeating itself. In September 1859 a geomagnetic storm, dubbed the Carrington event, caused interesting problems with the telegraph system.

Telegraph operators noticed that they could disconnect their batteries and work with just the induced currents from the storm – sometimes with improved results! To this day it is the most powerful coronal mass ejection on record. If a Carrington-level event were to happen now, it would cause widespread damage and disruption to power systems and satellites. As well as decimating electronics, any astronauts venturing beyond the protective blanket of Earth's geomagnetic field – such as to the Moon or Mars – would be in danger, something that NASA's upcoming Artemis lunar program needs to keep in mind.

Considering the stakes, coupled with the fact that the Sun is such a complex system, there must be another way to glean information about its

WHAT IS A SOLAR MAXIMUM AND SOLAR MINIMUM?

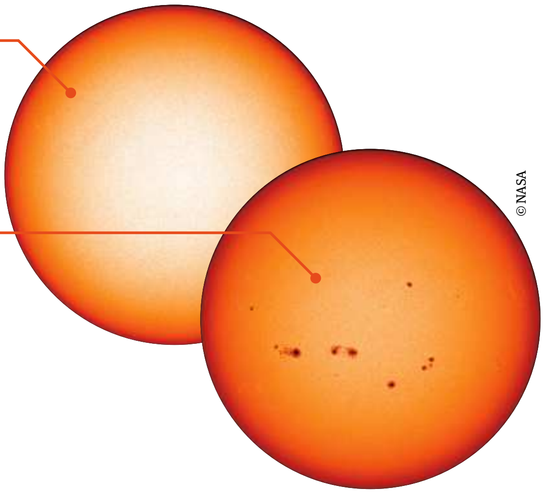
Solar maxima and minima happen some years apart, though at regular but varied intervals

SOLAR MINIMUM

The period within the 11-year solar cycle with the least activity. Very few solar flares and few – if any – sunspots are observed.

SOLAR MAXIMUM

The most active point in the solar cycle. Solar flares will manifest, as well as hundreds of individual sunspots, due to concentrated magnetic flux lines.



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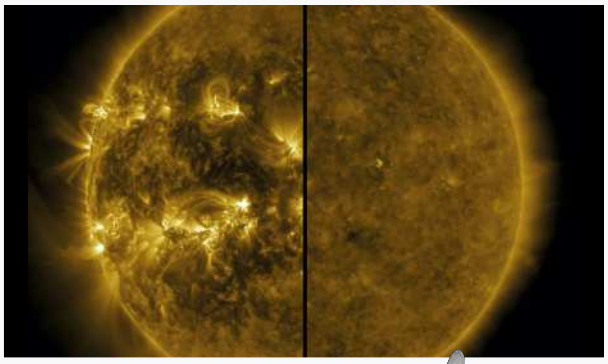
Below (clockwise from left): An active region with prominent magnetic loops, often visible during solar maxima

An active Sun at solar maximum (left) versus the Sun at solar minimum (right)

The Solar Dynamics Observatory studies many of the Sun's processes



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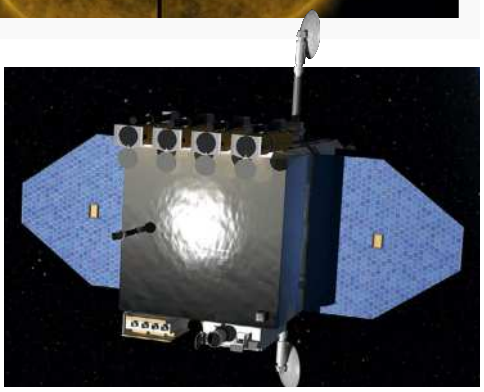

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future behaviour besides sunspots. Other tried-and-trusted methods exist, but there may well be another arrow in the quiver. A US-UK team led by Dr Scott McIntosh of the High Altitude Observatory at the National Center for Atmospheric Research in Boulder, Colorado, has looked at a related phenomenon to sunspot activity.

Using data from sources such as NASA's Solar Dynamics Observatory, the team looked at extreme ultraviolet and X-ray flashes in the solar corona. These so-called 'bright points' in the Sun's atmosphere correlate with large areas of material flowing in the Sun's interior, which rotates faster than surface plasma, similar to rates seen for sunspots. Dr Robert Leamon of the University of Maryland likens it to helium balloons being dragged along by weights attached to the bottom.

Such a study is potentially more useful than the sunspot cycle as it shows magnetic polarity. In the 19th century, Richard Carrington and Spörer both discovered sunspots appearing at different latitudes during different points in the solar cycle, starting at mid-latitudes and migrating towards the equator at the end. Plotted against time, this leads to a distinctive 'butterfly' diagram.

But in the early 20th century, American astronomer George Ellery Hale proved the importance of solar magnetism by showing how a complete polar flip actually spans two sunspot cycles: a flip, then a flip back. This 22-year Hale cycle is what McIntosh's team looks at. The bright points are markers of Hale cycle magnetic bands.

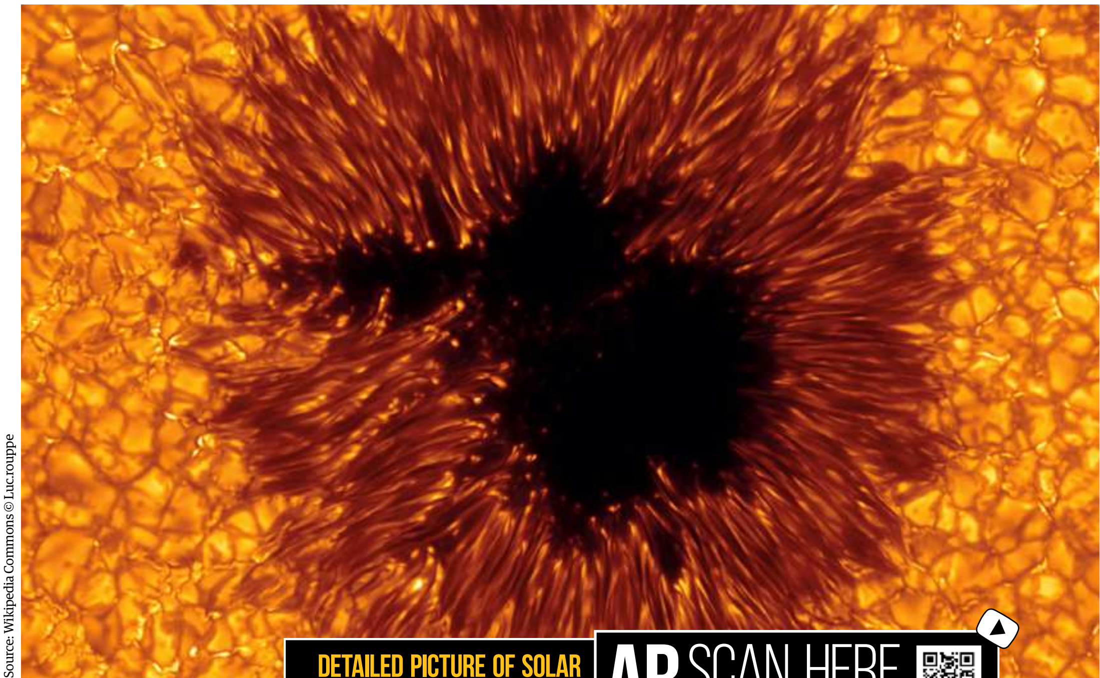
This begs the question of why the wider solar scientific community doesn't make more use of such observations in this way. "Folks have in the past – calling them ephemeral active regions – but predominantly they are locked into the 'big white whales' of solar activity: sunspots," says McIntosh. Just like sunspots, the magnetic bands travel the latitudes of the Sun to meet at the equator, annihilating in what McIntosh calls 'termination events'. His team uses these termination events to identify complete 22-year magnetic cycles, as well as the 11-year sunspot cycles of the past.

Using these alongside predictions made for a 2020 terminator event, the team predicts that Solar Cycle 25 will, in fact, be strong. In marked contrast to scientific consensus, they say it will be among the strongest few ever recorded.

Biesecker is supportive of the team's approach:

"THE SUN REALLY WANTS TO BE BALANCED, AND WHAT WE SEE IN TERMS OF SUNSPOTS IS THE RESULT OF IMBALANCE IN THAT PRESSURE"

SCOTT MCINTOSH



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DETAILED PICTURE OF SOLAR SURFACE WITH ANTON PETROV

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Above: Close-up view of a sunspot. Counting sunspots is the staple way of measuring solar activity

HOW ARE SUNSPOTS MADE?

Sunspots are a consequence of the Sun's magnetic field and complex fluid dynamics

1 STRAIGHT MAGNETIC FIELD LINES, FEW SUNSPOTS

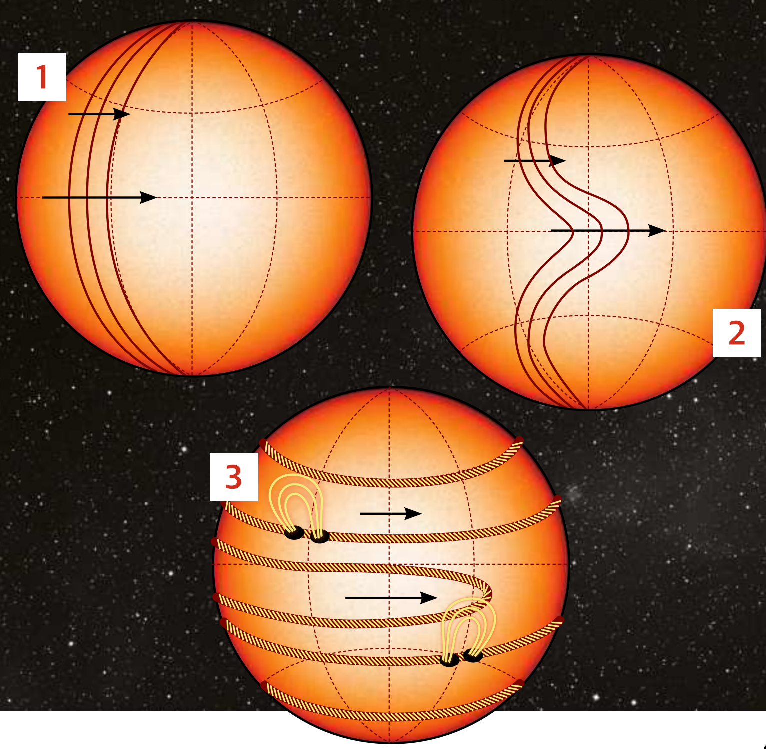
The Sun's global magnetic field lines start off straight, meaning few – if any – sunspots are visible. This occurs during, or close to, solar minimum.

2 FIELD LINES START TO BECOME DISTORTED

The Sun is not a solid body like Earth, composed instead from a fluid plasma. Its equator rotates faster than its poles, dragging field lines with it.

3 TWISTED TANGLES BREAK THE SURFACE

As the global field wraps around the Sun, concentrated magnetic loops break the surface, forming sunspots. These start at high latitudes.



OUR SUN

What goes on inside the mysterious powerhouse that dominates our Solar System?

SOLAR CORE

1 The Sun's thermonuclear fusion heart spans 27 times Earth's diameter. This is where hydrogen is fused into helium at huge temperatures and pressures, releasing energy.

RADIATIVE ZONE

2 Extending from the core to 70 per cent of the Sun's radius, energy propagates outwards via heat conduction and diffusion of electromagnetic radiation.

CONVECTION ZONE

3 Extending to just below the surface, the solar plasma's density reduces enough that material can move in a fluid way via convection currents.

PHOTOSPHERE

4 The Sun's visible surface is composed of convective cells, the upwellings and downfalls of the convection zone below. This gives the Sun its distinctive granular look.

CHROMOSPHERE

5 The Sun's thin lower atmosphere sits above the photosphere and extends to 3,000 to 5,000 kilometres (1,864 to 3,107 miles) above. Its deep-pink colour is visible during a total solar eclipse.

PROMINENCE

6 Hot plasma emanating from the photosphere, typically extending thousands of kilometres. Their structure comes from loops of magnetic field lines.

SUNSPOTS

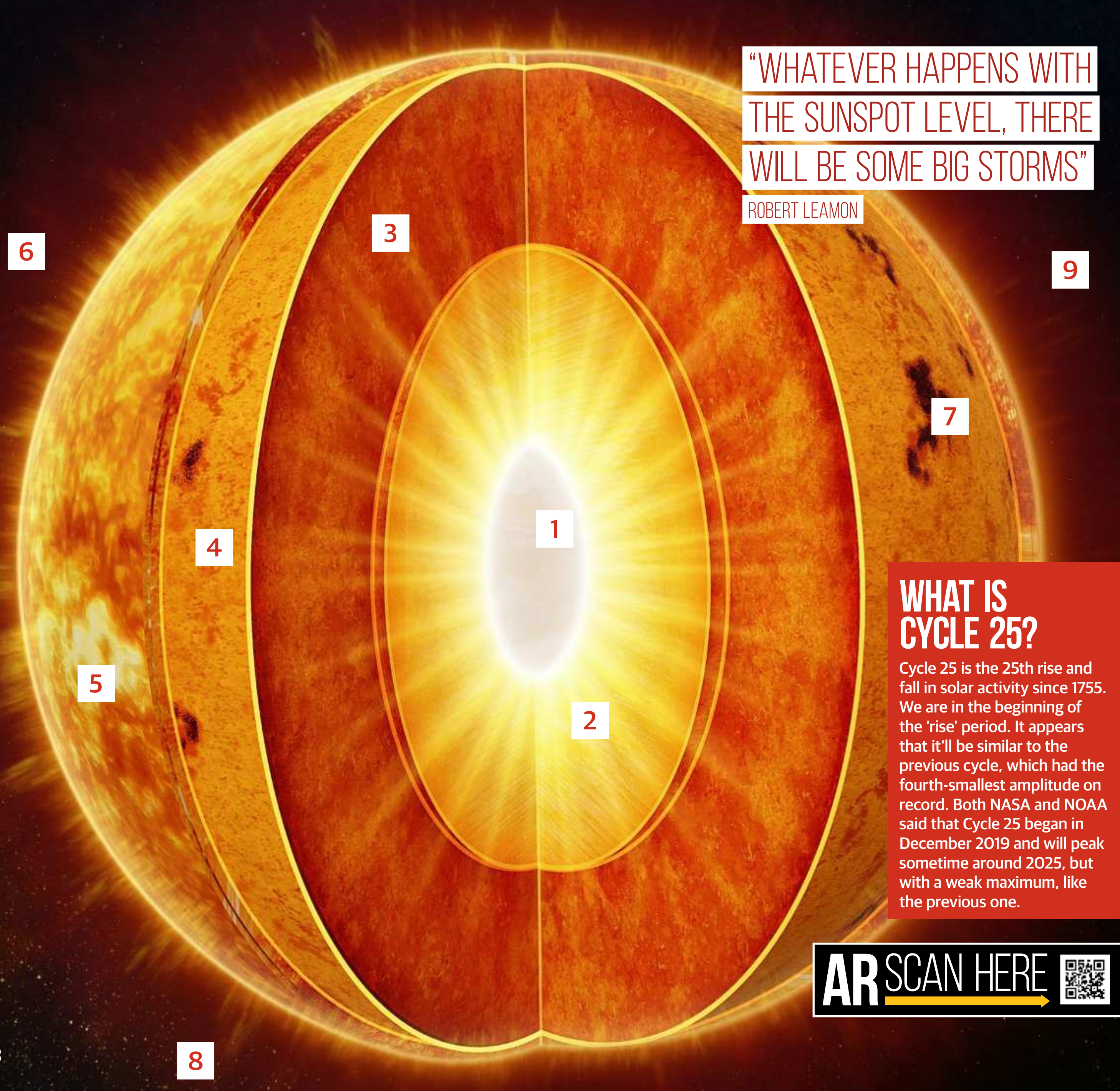
7 Concentrated magnetic fields inhibit convection wherever they punch through the surface. This reduces the temperature at those points, leading to relative darkening.

CORONAL HOLE

8 A sparse area of the Sun's upper atmosphere, the corona. Unfettered by any strong magnetic fields, solar particles stream out at twice the average rate.

CORONAL STREAMER

9 These bright magnetic loops of charged particles only tend to form at mid-latitudes. The solar wind stretches them into the coronal region.



> "WHATEVER HAPPENS WITH THE SUNSPOT LEVEL, THERE WILL BE SOME BIG STORMS"
>
> ROBERT LEAMON

WHAT IS CYCLE 25?

Cycle 25 is the 25th rise and fall in solar activity since 1755. We are in the beginning of the 'rise' period. It appears that it'll be similar to the previous cycle, which had the fourth-smallest amplitude on record. Both NASA and NOAA said that Cycle 25 began in December 2019 and will peak sometime around 2025, but with a weak maximum, like the previous one.

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"The work from McIntosh et al is very intriguing. It would be very exciting to have their prediction come true, as it would help teach us about how to better predict future solar cycles." But he does have a caveat. "The McIntosh technique has yet to make a true prediction. That is, one for which there is no knowledge of the future. It's very difficult for a panel to give much weight to a technique that is new, which has never made a prediction that can be tested." He says other more traditional methods continue to be used, as they have been successful in the past and are better known.

If McIntosh's study is right, however, what could it say about the solar interior? "That the magnetic systems inside the Sun are much stronger than we anticipate and that they interact strongly to shape the production of spots," says McIntosh. He says the pressure of the magnetic field band relative to the surroundings is important. "My sense is that the Sun really wants to be balanced, and what we see in terms of sunspots is the result of imbalance in that pressure – globally, locally and longitudinally." This means they think they're only seeing the tip of the iceberg where the magnetic field is concerned.

McIntosh goes on to say that the recurrence of 55 degree latitude bands in their analysis, which can be traced back through the entire observational and photographic record, is very overlooked. It suggests structural or geometric features that play a significant role in forming and aggregating the magnetic field in the Sun's interior.

The science still has many open questions. But is the team's approach bearing out for space weather forecasting? As Leamon says: "It's too early to tell, but so far the observed sunspot number and other measures, such as F10.7 solar radio flux [10.7 centimetre-wavelength radio waves] are tracking closer to our higher predictions rather than the lower panel consensus. Whatever happens with the sunspot level, there will be some big storms, and our technological society will be impacted in some way or another during Solar Cycle 25."

McIntosh concurs: "Indications are that it's on track to be bigger than 24, and likely 23 too. But we really need the termination event to happen to get real fidelity on the forecast." He's still convinced that it'll be a larger-than-average cycle, perhaps even in the top ten of every one on record. "But until that event happens, we won't know for sure."

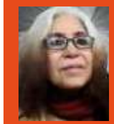
Biesecker's looking further ahead. "The relevance of the Hale cycle, as detailed in McIntosh et al, will be something for the Solar Cycle 26 Panel to consider." He points out that looking at the 22-year Hale cycle isn't new to forecasting, and that scientists have looked at the effects of odd and even cycles in the past, although with less skill than looking at precursors of the next immediate cycle. "Expect the McIntosh technique to be a big part of the conversation when the panel to forecast Solar Cycle 26 convenes," he tantalisingly concludes.

Kulvinder Singh Chadha
Space science writer
Kulvinder is a freelance science writer, outreach worker and former assistant editor of *Astronomy Now*. He holds a degree in astrophysics.

ON CYCLE 25

Solar scientist Madhulika Guhathakurta gives her personal view of our current solar cycle

DR MADHULIKA GUHATHAKURTA



A heliophysicist at NASA and leader of the Living with a Star Program. She started International Living with a Star in 2003. Presently on part-time detail at Goddard as senior advisor for new initiatives.

Guhathakurta gives her opinion as an individual and not as a representative of any organisation.

How unusual is Solar Cycle 25's sunspot activity?

Looking at sunspots as a non-physical index of solar activity, I think this solar cycle isn't unusual, especially in the context of the prior cycle. This cycle's sort of mimicking that. Even in the early 1800s and 1900s, you see cycles of this magnitude. During the Maunder minimum, when we couldn't detect any sunspots, the question remains how well could we detect very faint sunspots then or even now? We don't know and have no measure of that. The uncertainty associated with detecting no sunspots is much harder than counting them during solar maximum.

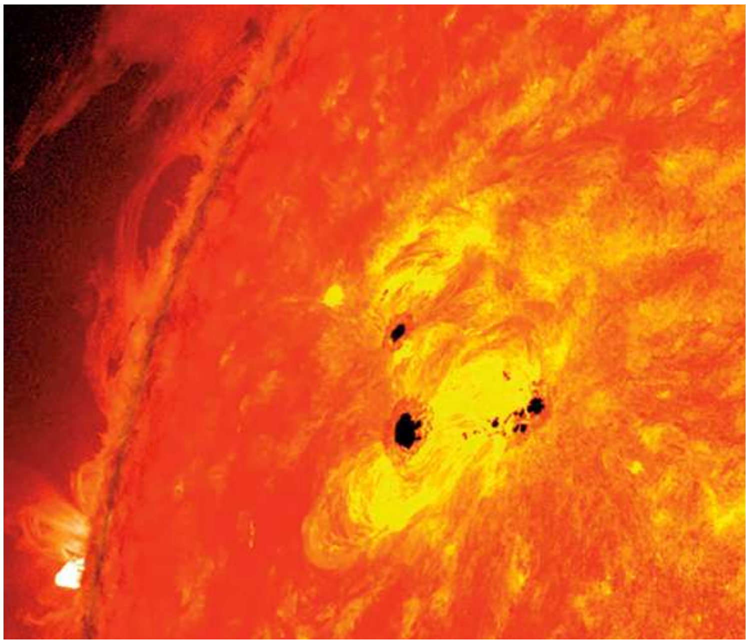
How does Cycle 25 fit with current knowledge?

Our present understanding is Babcock's solar dynamo model. Even though the details aren't well understood, it describes why we see what we see in terms of magnetic field activity, including the 11-year sunspot cycle. Inside the Sun, closed field magnetic loops are generated in the equatorial region, but open field lines at the poles in the corona become more dominant during solar minimum. Solar physicists agree that polar fields during solar minima dictate the strength of the next solar cycle. We can't measure polar field strength accurately, as we have to go outside the ecliptic plane. The Solar Orbiter mission from the European Space Agency, partnered with NASA, will give us a better estimate.

Are you seeing longer term trends?

The importance of these hasn't received proper scrutiny for lack of data. Beyond that I don't think we have a deeper understanding of the physics – there are many layers to go through. I spent the last four years at NASA Ames Research Center shaping a program called Frontier Development Lab and got fascinated by artificial intelligence and how we might utilise our data and the tools of AI to infer patterns that can better guide physics outcomes. Machine learning and AI could be critical for understanding solar variability and climate with huge amounts of data.

Below: Sunspots appear as dark patches on the tumultuous surface in this image taken by the Solar Dynamics Observatory



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PLANET PROFILE

MERCURY

The minute world is arguably the least explored of the four terrestrial planets

Mercury is a planet that has sculpted not only our scientific understanding over generations, but also our culture. Mercury has been mentioned in texts dating as far back as the 2nd millennium BCE by the Sumerians, and the ancient namesake of the planet is the Roman messenger god, Mercury.

Mercury is the smallest of all the true planets in the Solar System and the closest planet to the Sun, but there is so much more to it. Mercury is so tiny compared to the other planets that you can actually fit around 23,500 Mercurys into Jupiter, and it is roughly 1,400 kilometres (870 miles) larger in diameter than the Moon. The small planet also orbits the Sun with less than half the distance between the Sun and the Earth, resulting in it being 'tidally locked'.

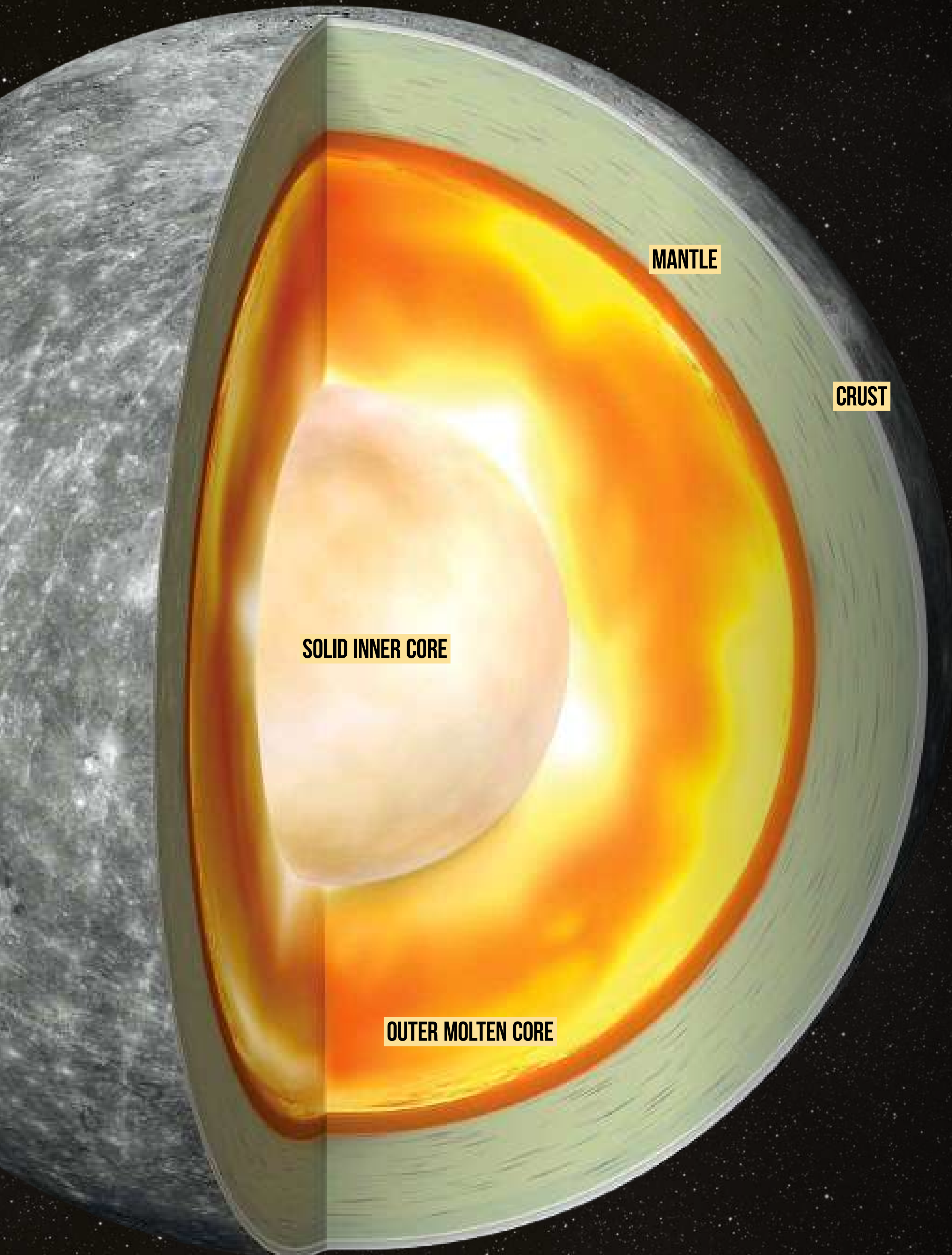
Tidal locking occurs when an object is so close to its host object that the gravity is overwhelmingly powerful, and instead of continuously spinning on its axis, like Earth does, the object has one side facing towards the host object at all times. In this case Mercury is tidally locked to the Sun, and for every two revolutions around the Sun, Mercury rotates on its axis three times. Each orbit takes 88 Earth days, making a year on Mercury roughly a quarter of an Earth year.

Because Mercury is so close to the Sun, the surface temperatures on the little planet can be scorching, reaching highs of 450 degrees Celsius (840 degrees Fahrenheit). Enduring this bombardment of radiation from the Sun, the planet also struggles to keep hold of its atmosphere, meaning that no heat is trapped. This means the night side of the planet – the one facing away from the Sun – can have temperatures as low as -180 degrees Celsius (-290 degrees Fahrenheit).

While Mercury is a similar size to the Moon, it is also similar in appearance. It is a heavily cratered, rocky body with some of the largest craters in the Solar System. One crater studied by previous exploration missions is a great example. The Caloris basin, which is roughly 1,550-kilometres (960-miles) wide, is about the size of Texas, and was formed when an asteroid about 100 kilometres (60 miles) across hit Mercury's surface 4 billion years ago, impacting the planet with energy equivalent to a trillion one-megaton bombs.

If you scratch beneath the surface, the true weirdness of Mercury starts to become apparent. Under the ultra-thin cratered crust is an extremely dense planet, with somewhere between 70 and 85 per cent of the planet being an enormous iron core. Astronomers have spent years constraining whether it is solid, molten or both, and they seem to agree it has a solid iron core with an outer molten core. Astronomers believe that a molten core could explain Mercury's very weak magnetic field. However, after the results were brought back and analysed from NASA's Mariner 10 and MESSENGER space probes, astronomers now believe that Mercury is the exposed core of a much larger planet, with its outer layers lost to a powerful collision billions of years ago.

"ASTRONOMERS NOW BELIEVE THAT MERCURY IS THE EXPOSED CORE OF A MUCH LARGER PLANET, WITH ITS OUTER LAYERS LOST TO A POWERFUL COLLISION"



ATMOSPHERIC COMPOSITION

42%
OXYGEN

29%
SODIUM

22%
HYDROGEN

6%
HELIUM

0.5%
POTASSIUM

+

TRACES OF ARGON, CARBON DIOXIDE, WATER, NITROGEN, XENON, KRYPTON, NEON, CALCIUM, MAGNESIUM

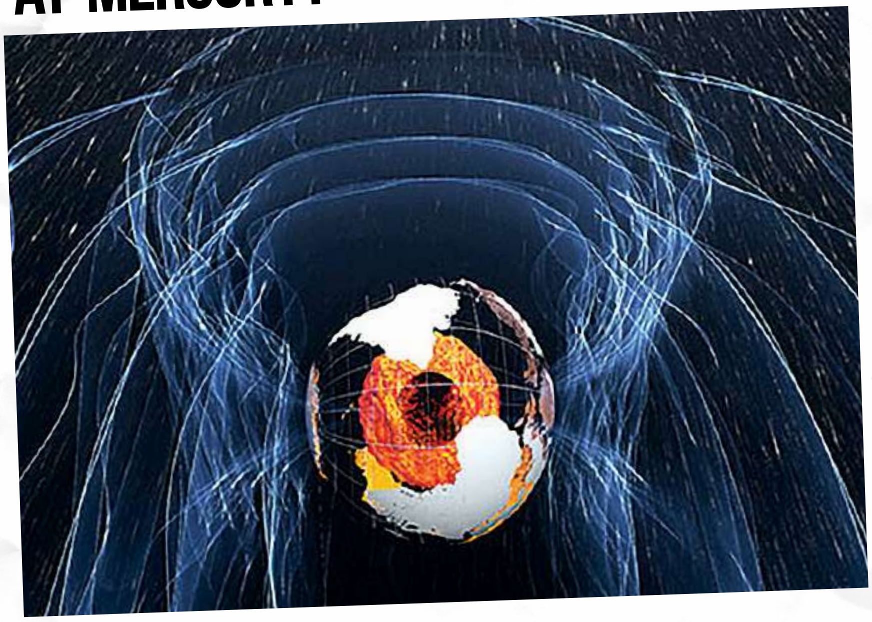
WHAT'S BEEN HAPPENING AT MERCURY?

MERCURY'S MAGNETIC IRREGULARITIES

A magnetic field is the result of the motion of an internal molten core, and that is certainly the case on Earth. Earth's magnetic poles have also been known to shift in location from time to time, but now astronomers have suggested that Mercury's ancient magnetic poles have been doing the same thing.

Mercury's ancient magnetic poles, known as paleopoles, appear to have shifted throughout time, and this could present clues in the investigation of Mercury's interior. By understanding the magnetic field, astronomers could pinpoint the nature of the planet's molten core. "There are several evolution models of the planet, but no one has used the crustal magnetic field to obtain the planet's evolution," says Joana S. Oliveira, an astrophysicist at the European Space Agency's European Space Research and Technology Centre in Noordwijk, the Netherlands.

These results came from NASA's MESSENGER data collected on ancient craters that had irregular magnetic signatures. Not only would a further analysis help us understand the nature of Mercury's interior, it could have implications for understanding how the planet evolved, and even how Earth's magnetic field evolved.



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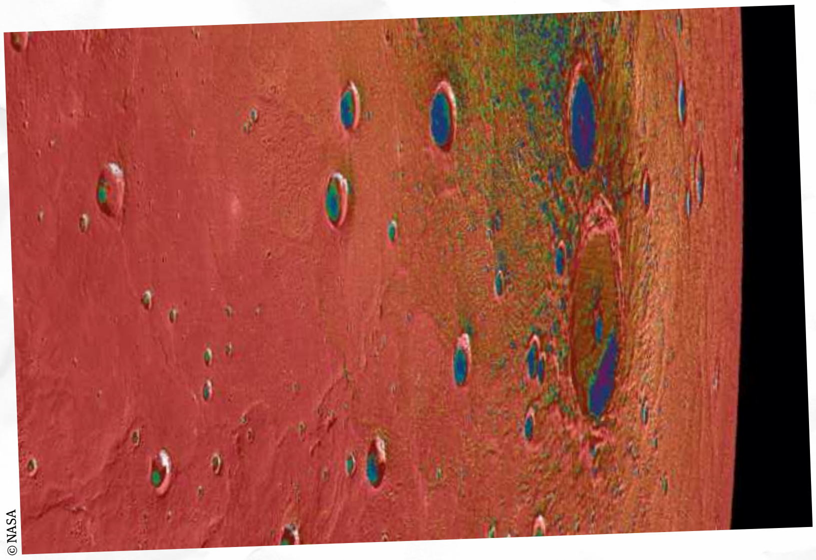

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AN INSULATING BLANKET OF IRON SULPHIDE

Once again Mercury's magnetic field is the centre of astronomers' research. However, instead of trying to understand the nature of it, astronomers are trying to understand how it is kept in place. Astronomers have seen with Mars how a planet much smaller than Earth can solidify and lose its molten core, and consequently lose its magnetic field, but Mercury still appears to have one.

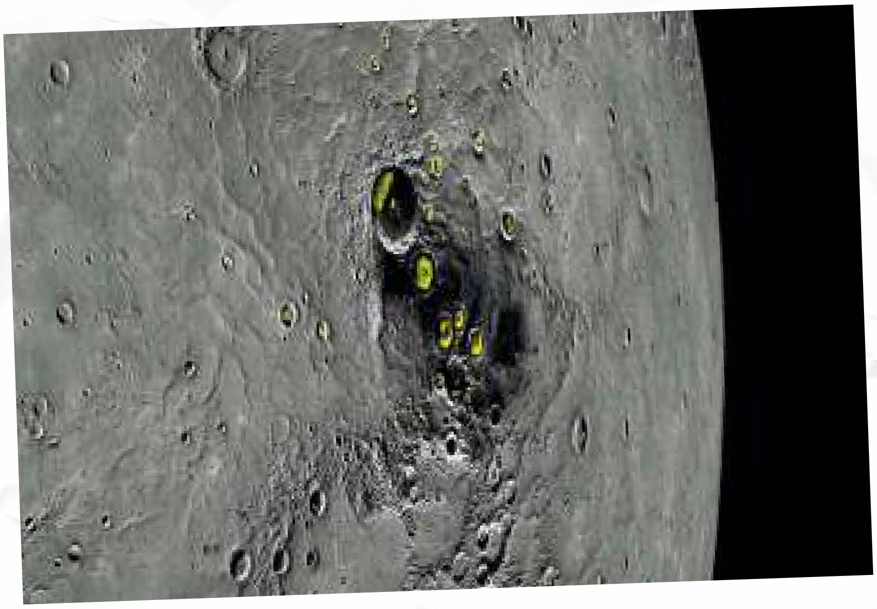
This recent research suggests that a layer of iron sulphide could be insulating the core, maintaining its molten state. "Based on lab experiments, we got some data to explain how actually you can generate such a low magnetic field and sustain it for such a long time," says mineral physicist Geeth Manthilake of Clermont Auvergne University in Clermont-Ferrand, France.

These experiments predict that Mercury has a solid inner core, with a molten outer core of iron, sulphur and silicon. Much like water and oil, these elements can't mix, so the iron and sulphur compounds were expelled towards the outer regions of the planet and created the insulating layer.

SEARCHING FOR WATER ICE ON MERCURY

The search for water elsewhere in the Solar System has become more of a hunt among astronomers as engineers and scientists alike keep a keen eye out for its cosmic signature and prepare for a mission to the Moon's poles. Mercury is another body that astronomers suspect is hiding the valuable comodity at its poles, with NASA's MESSENGER space probe revealing the signatures of thick deposits of water ice hidden in craters at the planet's poles. In these craters, sunlight doesn't reach the depths within, and therefore they're sheltered from the radiation that could cause water ice to dissipate. Astronomers believe these craters could hold answers about where water is dispersed throughout the Solar System and even the origins of life itself.

Astronomers have also been comparing Mercury and the Moon to try and understand what the water ice in these craters may look like. This involved looking at about 14,000 craters on the two bodies, over 2,000 of which are on Mercury. They have come to the conclusion that on the Solar System's smallest planet, craters that harbour ice have shallower sides than those that don't.



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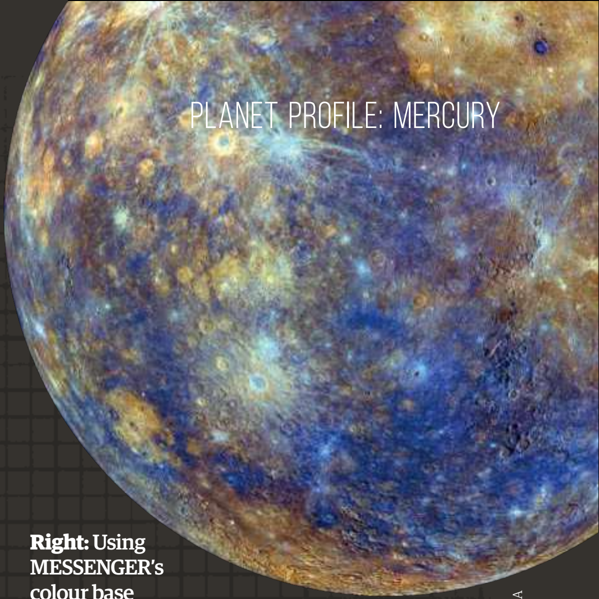

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EXPLORING THE PAST AND FUTURE OF THE SWIFT PLANET

Visiting Mercury is a dangerous and difficult task. Some may think that this is because it's a relatively small planet and therefore more difficult to navigate to, but that is far from the case. The voyage to Mercury is difficult because of the humongous ball of searing plasma, the Sun, and its pesky gravity. Navigating a spacecraft to Mercury requires propulsion that will get it to Mercury and also counteract the gravity of the Sun so the craft doesn't go falling into the surface and burn up. This is why only two spacecraft have ever visited the small terrestrial planet.

NASA has been the operator of both of these missions, the first being Mariner 10 in 1974, which conducted a series of flybys and gathered close-up images. However, the mission that brought the most consistent and fascinating results is the MESSENGER (MErcury Surface, Space ENvironment, GEochemistry, and Ranging) spacecraft, which is the first and only spacecraft so far to orbit the planet. MESSENGER's most important results included how volatile-rich the planet was – volatiles being chemical compounds with low boiling points – which has important implications for the planet's formation. Also there were its ice deposits at the poles, its weird magnetic field offset and its irregular depressions called 'hollows'.

The next mission to Mercury is the exciting BepiColombo, a joint endeavour by the European Space Agency (ESA) and the Japan Aerospace Exploration Agency (JAXA). This mission will arrive at Mercury in 2025, where it will separate into two orbiters and use its impressive instrumental suite to investigate the planet from all angles.

The Mercury Planetary Orbiter (MPO) was built and will be operated by the ESA, and the Mercury Magnetospheric Orbiter (Mio) was built and will be operated by JAXA. This unique mission will have its two orbiters working simultaneously as scientists get up-close observations of the surface and far-away observations of the magnetic field.

© NASA

Right: Using MESSENGER's colour base map imaging, Mercury is shown in a colourful contrast

Left: MESSENGER spent the best of four fruitful years at Mercury

Below: The Van Eyck crater is just one of the many enormous craters on Mercury

BEPICOLOMBO'S SEVEN-YEAR JOURNEY TO MERCURY

- **Date:** 20 October 2018
  Activity: Launch from Earth
- **Date:** 13 April 2020
  Activity: Earth flyby
- **Date:** 16 October 2020
  Activity: First Venus flyby
- **Date:** 11 August 2021
  Activity: Second Venus flyby
- **Date:** 2 October 2021
  Activity: First Mercury flyby
- **Date:** 9 January 2025
  Activity: Sixth Mercury flyby
- **Date:** 5 December 2025
  Activity: Orbital insertion around Mercury

MERCURY FACTS

0

Mercury has no moons, making it one of two planets in the Solar System – along with Venus – to not have its own moon.

Mercury's atmosphere is more comparable to a 'thin exosphere', as it is comprised mostly of atoms ejected from the surface due to the solar wind and meteoroid impacts.

If someone was standing on Mercury's night side at the right time of year, they would see a faint orange glow from the sodium scattered by sunlight.

One day on Mercury lasts 59 Earth days – an incredibly long time in comparison – while a year on Mercury lasts just 88 Earth days.

NASA's MESSENGER mission stayed in orbit around Mercury from March 2011 to April 2015 before crashing into the surface of the planet.

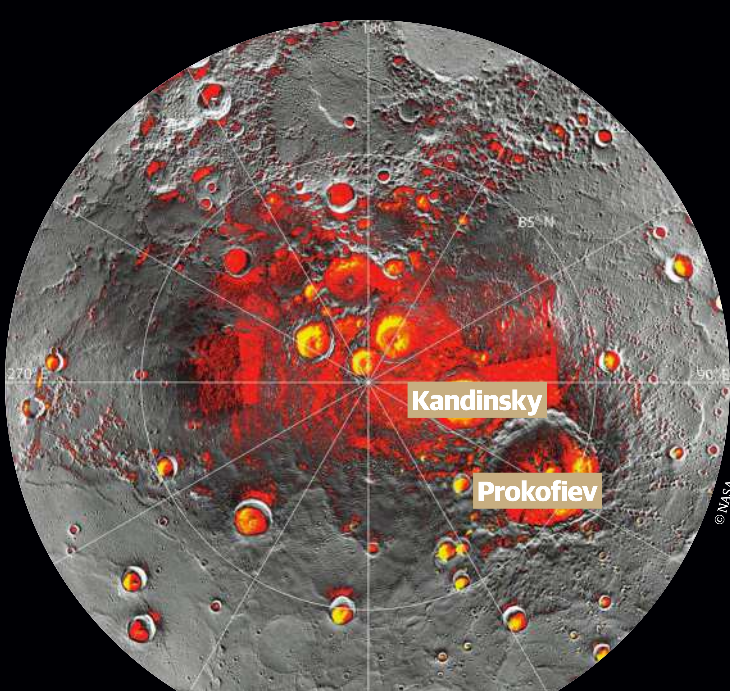
Astronomers believe there was active volcanism on Mercury at some point, as there are areas that appear to have been flooded with lava.

© NASA

WHAT'S NEW AT MERC

Scientists are still busy analysing data from the MESSENGER mission – and it has plenty of surprises

Reported by Andrew May



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ICE ON A HOT PLANET

▶ A view of the area around Mercury's north pole, with regions that permanently lie in shadow shown in red and suspected traces of ice shown in yellow.

URY?

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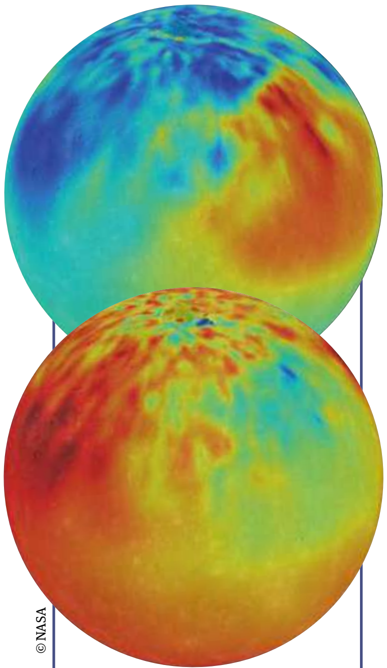

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ELEMENTS THAT 'SHOULDN'T BE THERE'

▲ MESSENGER's instruments included spectrometers to analyse the chemical composition of Mercury's surface – they discovered a surprisingly high level of volatile elements such as sulphur and potassium.

A GIANT CANNONBALL

▶ Mercury's structure is dominated by its huge iron core. Like Earth's, it's molten in the outer parts – which is where the magnetic field originates – and solid at the centre.

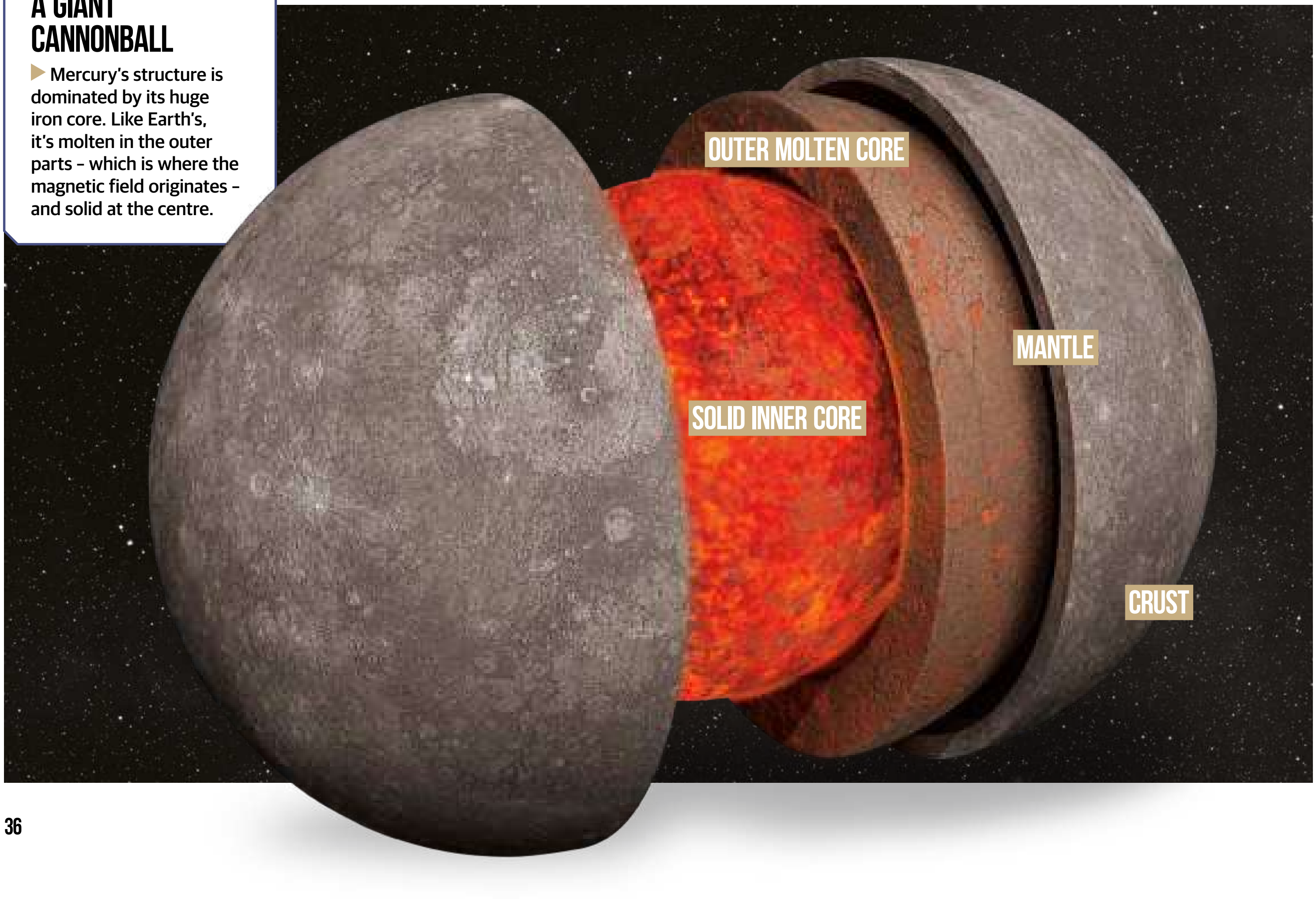
Which planet is Earth's nearest neighbour in the Solar System? The obvious answer is Venus, which makes the closest approach to us – but it spends half its orbit on the other side of the Sun, when it's further away from us than Mercury. It was only last year that Tom Stockman, a graduate research assistant at Los Alamos National Laboratory, New Mexico, and colleagues crunched the numbers to work out which planet is actually closest on average – and they were as surprised as anyone by the answer: "When averaged over time, Earth's nearest neighbour is in fact Mercury," they wrote.

Despite its proximity, Mercury has always been a mysterious planet due to the difficulty of observing it through Earth-based telescopes. That's down to a combination of its small size and the fact that it never gets very far from the Sun in the sky. The only time it makes a really spectacular sight, in fact, is when it passes directly in front of the Sun during a transit of Mercury – like the one that took place a few months ago in November 2019.

If Mercury is a difficult planet to observe from Earth, it's not an easy destination for spacecraft either. That's partly because a spacecraft speeds up under the effect of gravity as it falls towards the Sun – and then its rocket engine has to work hard to lose that excess speed when it gets to Mercury. Another problem is the extreme heat – well over 400 degrees Celsius (752 degrees Fahrenheit) – in the vicinity of Mercury, which poses serious challenges for spacecraft designers. Since the dawn of the space age, only two space probes have been to Mercury – Mariner 10 in the 1970s, followed by MESSENGER more recently, both by NASA.

The photographs sent back by Mariner 10, which made three close passes of Mercury in 1974 and 1975, revealed a desolate, crater-studded landscape that looks a lot like our Moon. But the mission had a surprise for scientists in its discovery of a well-defined magnetic field around the planet. It's a hundred times weaker than Earth's field, but Venus and Mars don't have internal magnetic fields at all, and Mercury wasn't expected to either.

A closer look at Mercury's magnetic field was one of the key objectives of NASA's follow-up mission, MESSENGER, which entered orbit around the planet in March 2011. It remained there until it ran out of manoeuvring propellant four years later – and in the final few months the mission controllers got increasingly bold. They dipped the spacecraft to just 15 kilometres (9.3 miles) above the planet, allowing them to measure relic magnetism in the surface rocks. "The signals we detected are really small, and very hard to measure," explains planetary geophysicist Catherine Johnson. "We'd never have been able to measure them if not for these really



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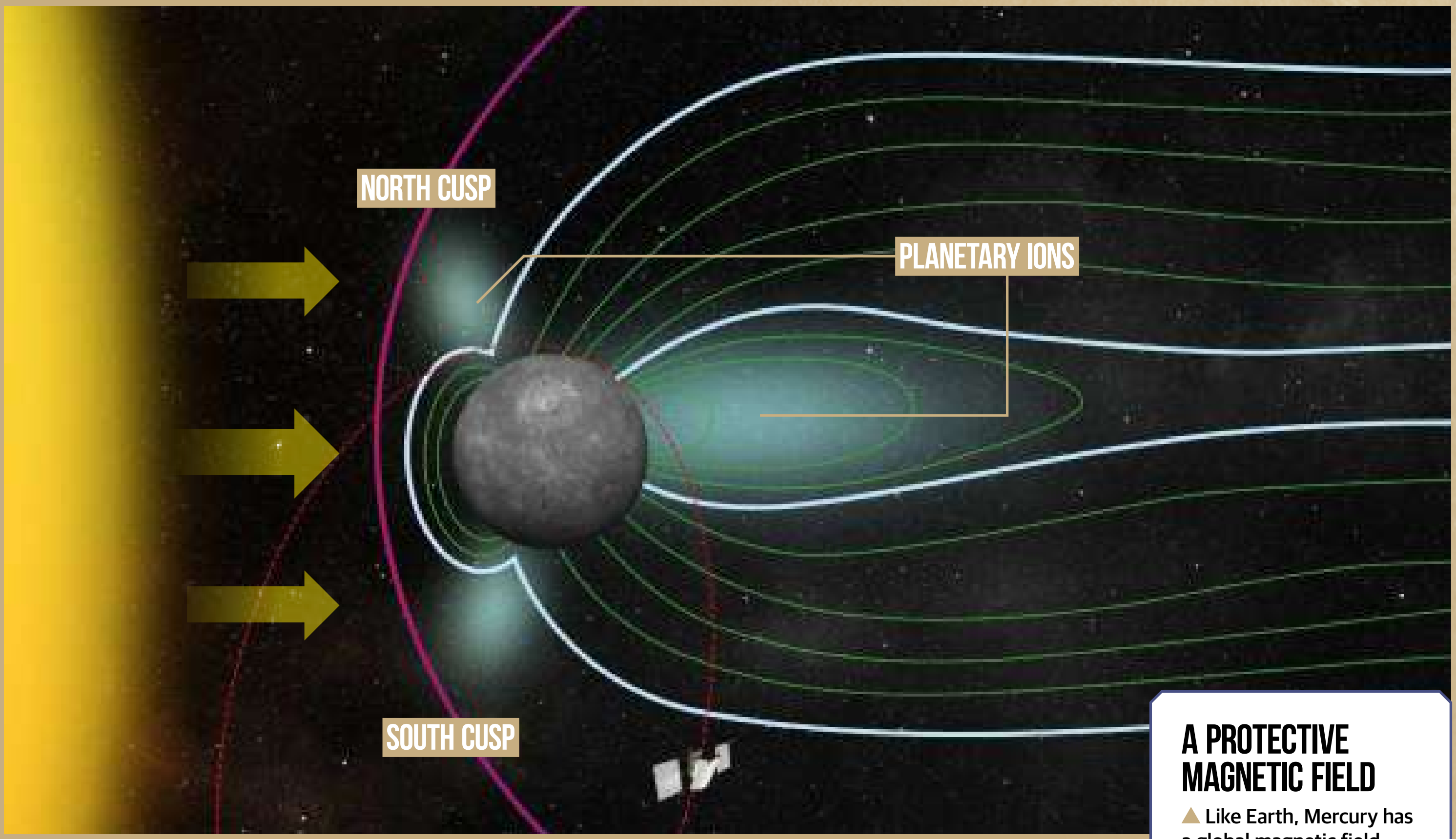
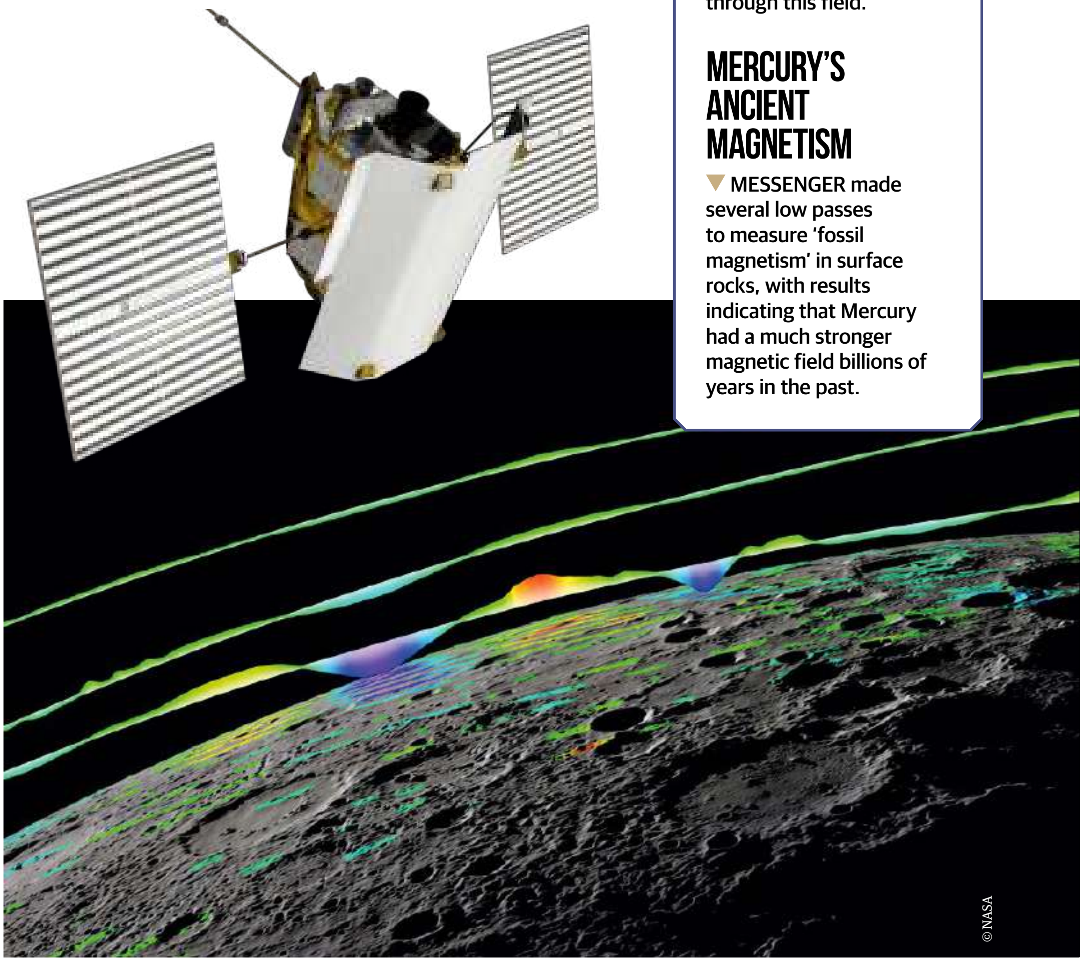


A PROTECTIVE MAGNETIC FIELD

▲ Like Earth, Mercury has a global magnetic field which helps to shield it from the solar wind. The dashed red line shows MESSENGER's orbit through this field.

MERCURY'S ANCIENT MAGNETISM

▼ MESSENGER made several low passes to measure 'fossil magnetism' in surface rocks, with results indicating that Mercury had a much stronger magnetic field billions of years in the past.



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"WE'D NEVER HAVE BEEN ABLE TO MEASURE THEM IF NOT FOR THESE REALLY RISKY LOW-ALTITUDE OBSERVATIONS" CATHERINE JOHNSON

risky low-altitude observations in the last few months of the MESSENGER mission."

The measurements indicated that not only is Mercury's magnetism very old - going back at least 3.8 billion years - but it was much stronger in the past, "comparable to the strength of Earth's magnetic field today," according to Johnson.

When all its propellant was used up, MESSENGER was deliberately crashed into Mercury's surface - the first Earth-made artefact on the planet - on 30 April 2015. From NASA's point of view the mission was a huge success, repeatedly surprising researchers with its discoveries. "In the end, most of what we considered to be gospel about Mercury turned out to be a little different than we thought," as mission scientist William McClintock said at the time.

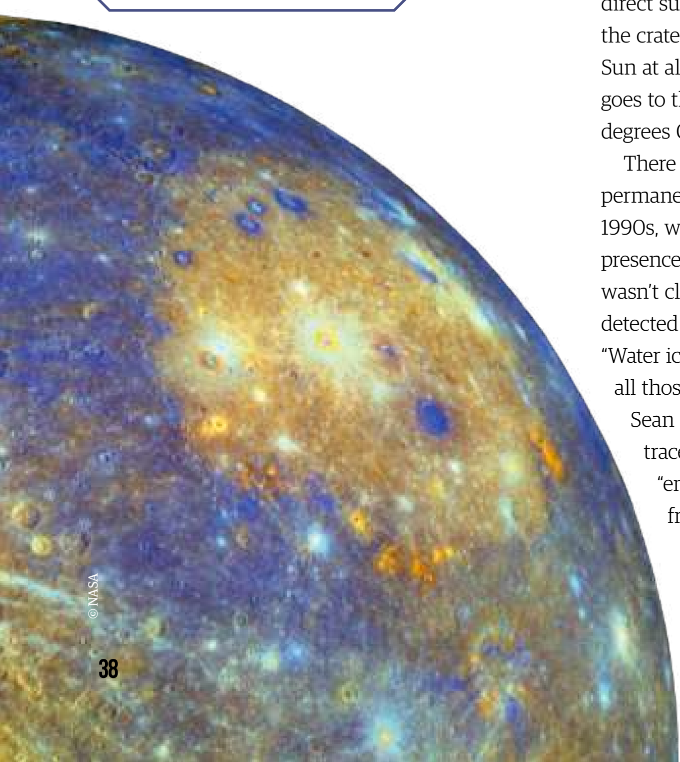
© Adrian Mann

ON COURSE FOR MERCURY

The two spacecraft making up the exciting BepiColombo mission, from the European and Japanese space agencies, were launched in October 2018 and should go into orbit around Mercury in late 2025.

RETHINKING MERCURY'S ORIGIN

It used to be thought that Mercury suffered a huge impact which stripped off its outer layers, but that's less likely now we know there are volatiles on the surface.



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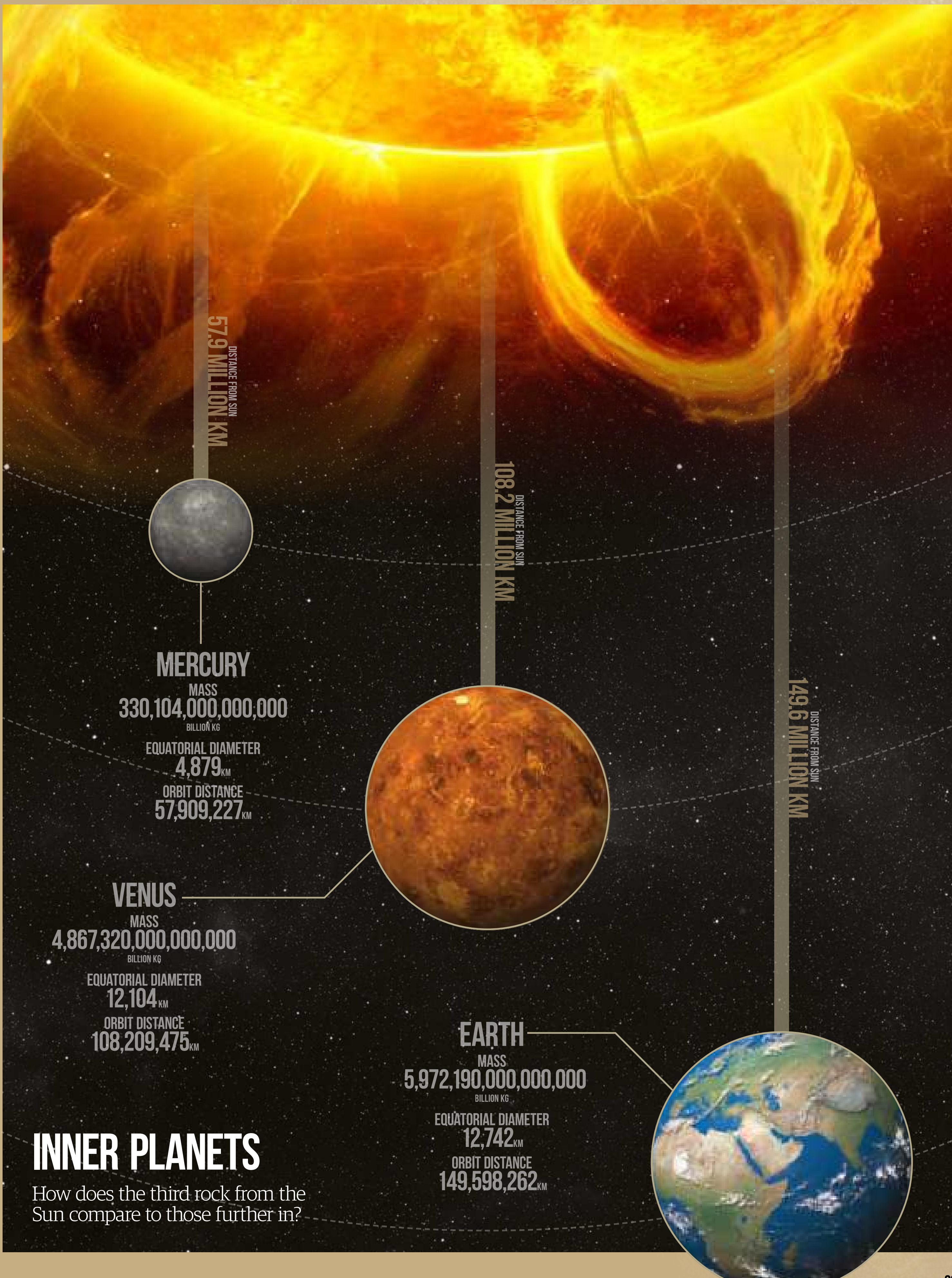
"MOST OF WHAT WE CONSIDERED TO BE GOSPEL ABOUT MERCURY TURNED OUT TO BE A LITTLE DIFFERENT THAN WE THOUGHT" **WILLIAM MCCLINTOCK**

Among MESSENGER's biggest surprises was the discovery of water ice on Mercury. This seems odd, given the extremely high surface temperatures in direct sunlight. But there are spots inside some of the craters near the planet's poles that never see the Sun at all, and consequently the temperature there goes to the opposite extreme – closer to minus 200 degrees Celsius (minus 328 degrees Fahrenheit).

There had been hints of ice inside these permanently shadowed craters as long ago as the 1990s, when radar measurements indicated the presence of highly reflective material. The issue wasn't clinched, however, until MESSENGER detected hydrogen atoms in the same locations. "Water ice is the only candidate we've got that fits all those observations," as principal investigator Sean Solomon explained. It's not just a few traces of ice, either – according to Solomon it's "enough ice to encase Washington DC in a frozen block two-and-a-half miles deep".

Another unexpected finding was a brand-new type of surface feature that isn't seen anywhere else in the Solar System except Mercury. Called 'hollows', these are shallow depressions found inside many of the planet's craters. They're believed to have formed when volatile components in the surface material evaporated, causing the remaining material to collapse. "The hollows are one of the most viscerally interesting discoveries from the mission," according to another MESSENGER scientist, Steve Hauck. "They were completely unexpected – a new landform, and one that appears to form by loss of rock to space."

The idea that volatile materials boiled off Mercury in the distant past seems reasonable enough, given its hot location close to the Sun. What would be more surprising would be to find volatile materials still on the planet's surface today – and yet that's exactly what MESSENGER did find. It's a subject Brian Cox talked about in his TV series *The Planets* last year. "The discovery of relatively large concentrations of elements like sulphur and potassium on Mercury's surface was a huge surprise," he said. "So Mercury is an enigma, and discoveries like these force us to completely



INNER PLANETS

How does the third rock from the Sun compare to those further in?

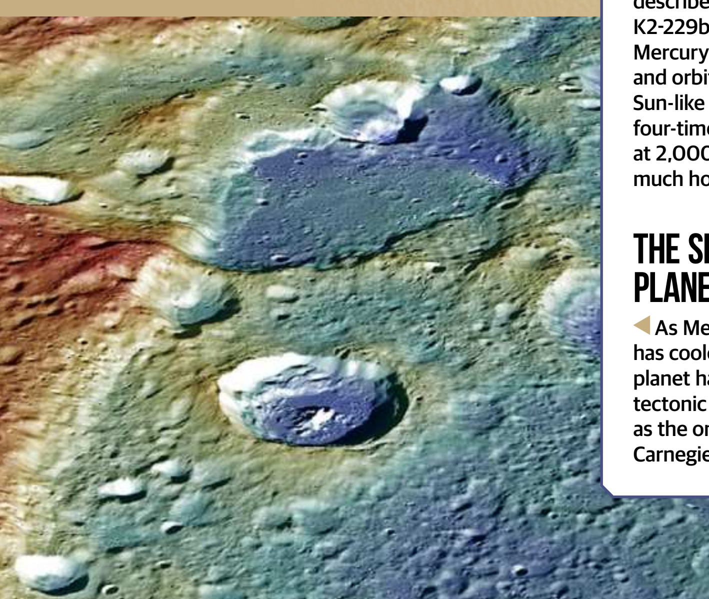
rethink our theories about the formation of the planet."

The problem with this new discovery was that it didn't fit in with existing ideas about Mercury's origin, which had been developed over the years to explain its unusual internal structure. Like Earth, the planet is made up of a rocky crust and mantle surrounding an iron-rich core – but in Mercury's case the core is huge, making up almost 85 per cent of its volume. For a long time it was assumed that Mercury must have started out looking very similar to Earth in size and composition. Then, billions of years ago, it had its outer layers knocked off in a collision with a huge asteroid.

The problem with that theory is it doesn't explain why there's so much sulphur and potassium on Mercury's surface today. It now seems likely that Mercury formed much as it is now, and that its large core was a consequence of the different physical conditions in the inner parts of the early Solar System compared with further out where the other planets formed. That's supported by the discovery of exoplanets orbiting close to other Sun-like stars, which also appear to have large metallic cores like Mercury.

Despite its numerous discoveries, MESSENGER left plenty of unanswered questions – but fortunately there's another mission, BepiColombo, on its way to Mercury right now. Made up of two separate spacecraft, the ESA's Mercury Planetary Orbiter and the Japan Aerospace Exploration Agency's Mercury Magnetospheric Orbiter, it's due to arrive in 2025. With 16 scientific instruments, researchers are hoping BepiColombo will make just as many discoveries as MESSENGER did.

"THE DISCOVERY OF RELATIVELY LARGE CONCENTRATIONS OF ELEMENTS LIKE SULPHUR AND POTASSIUM ON MERCURY'S SURFACE WAS A HUGE SURPRISE" **BRIAN COX**



A NEW TYPE OF FEATURE

These rounded depressions in Raditladi Basin are examples of 'hollows' – features unique to Mercury which may have been formed when volatile materials evaporated into space long ago.

MERCURY ON STEROIDS?

That's how NASA described exoplanet K2-229b, which resembles Mercury in being iron-rich and orbiting close to a Sun-like star, but it's four-times bigger and, at 2,000°C (3,632°F), much hotter.

THE SHRINKING PLANET

As Mercury's interior has cooled down, the planet has shrunk, creating tectonic fault lines such as the one pictured here, Carnegie Rupes.

x3 Images © NASA

VEN

22 THINGS YOU DID

Earth's sister planet is an intriguing and mysterious world, with more to it than meets the eye

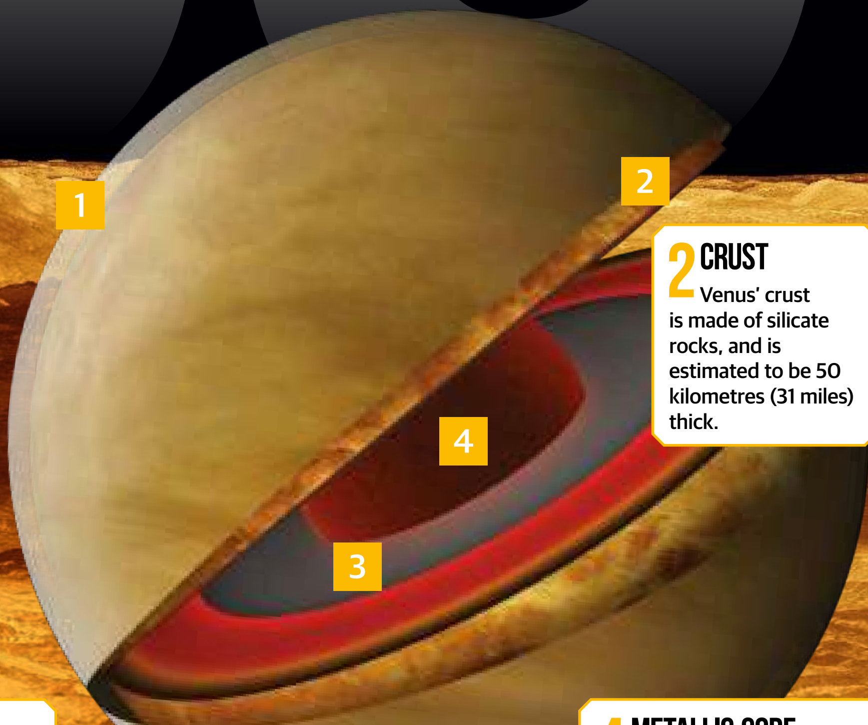
Written by Lee Cavendish

1 VENUS HAS A RICH HISTORY

Studies of Venus can be traced back to the ancient Babylonians in 1600 BCE. They tracked the movement of several planets and stars. The oldest astronomical document on record is a Babylonian diary of Venus appearances over a 21-year period. Venus played a serious part in the mythology of ancient civilisations, including the Mayans and Greeks. The name 'Venus' comes from the Roman goddess of love and beauty.

NUS

N'T KNOW ABOUT



1 ATMOSPHERE
96.5 per cent of Venus' atmosphere is carbon dioxide, with the remainder being nitrogen, sulphur dioxide, argon and traces of water vapour, carbon monoxide, helium and more.

2 CRUST
Venus' crust is made of silicate rocks, and is estimated to be 50 kilometres (31 miles) thick.

3 MOLTEN MANTLE
The heat from the core creates a molten mantle that is 3,000-kilometres (1,200-miles) thick.

4 METALLIC CORE
Venus' iron core consists of a solid inner and liquid outer core roughly 3,200 kilometres (2,000 miles) in radius.

2 THE PRESSURE'S ON!

Walking around Venus would be an unbearable experience for several reasons, but one of them is the extreme pressures on the surface. The atmosphere creates air pressure that is over 90 times the air pressure on Earth, which is similar to the pressure around a kilometre (0.6 miles) deep in the ocean.

3 IT'S JUST LIKE OUR EARTH

When looking purely at the physical parameters of Venus, it is remarkably similar to Earth. They are both almost the same in size and density, their compositions are similar and they both appear to have relatively young surfaces that are surrounded by an atmosphere with clouds. It's worth stating that Venus' clouds are primarily sulphuric acid though, which isn't something that you'd want raining down on you!

4 IT HAS MANY PHASES

Venus experiences different phases, just like the Moon. As Venus travels around the Sun within the orbit of Earth, it changes between a 'morning star' and 'evening star' roughly every nine-and-a-half months. During this period it shifts between different percentages of illumination, a trait that everyone normally associates with the Moon.

5 TRANSITS ARE VERY RARE

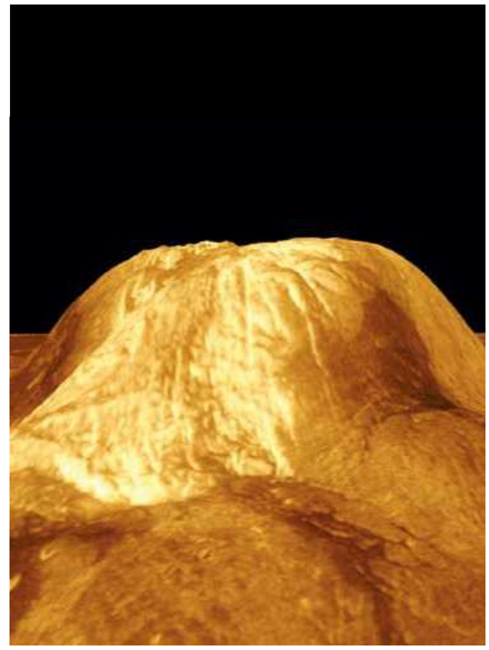
Venus is one of two planets that orbit the Sun within the orbital path of Earth. Along with Mercury, these two planets can find themselves between Earth and the Sun, sometimes creating a silhouette that moves across the Sun over a period of hours. These journeys are known as 'transits', and Venus is known to transit in pairs, with over a century separating the pairs, making it a very rare event.

6 IT'S HELLISHLY HOT

Venus is the hottest planet in the Solar System, even hotter than the dayside of Mercury, which has temperatures of 427 degrees Celsius (801 degrees Fahrenheit). Because of Venus' thick, carbon dioxide-rich atmosphere, the heat is efficiently retained, creating surface temperatures higher than 470 degrees Celsius (880 degrees Fahrenheit).

7 VENUSIAN VOLCANICITY

To add to the hellish image of Venus, it also has the most volcanoes present on the surface of all planets in the Solar System. On Earth there are 1,500 known active volcanoes, and Mars is best known for the largest volcano in the Solar System, Olympus Mons. However, Venus has over 1,600 known major volcanoes, and that's not including the smaller ones or any that haven't been detected yet.



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8 WHY IT DOESN'T HAVE A MOON

Venus and Mercury are the only planets in our Solar System that do not have their own moon. It's a bit more understandable as to why Mercury doesn't have a moon, because its close proximity to the Sun has a negative effect on any contenders, and it is even smaller than some known moons such as Jupiter's Ganymede and Saturn's Titan. However, researchers have argued that the reason Venus doesn't have a moon isn't as simplistic. There are two theories: the first is that any moon that Venus had was stolen by the Sun's gravity. The second is known as the 'double-impact theory', which states that a large celestial body hit Venus billions of years ago and created a moon, in a similar way to how Earth got its lunar companion. But several million years later, an even bigger object hit Venus, causing the retrograde rotation, weakening the tidal forces and sending the moon to sink into Venus, never to be seen again.

9 EARTH VS VENUS

What are the similarities and differences between the second and third planet from the Sun

The Sun

On Venus, the Sun would appear no more than a dimly glowing patch through the thick clouds and everlasting overcast weather.

Clouds

Venus is enveloped in clouds, not allowing any nosey astronomers to investigate the surface. While the Earth is also hidden by clouds, much more of our planet's surface is visible from space.

Surface rocks

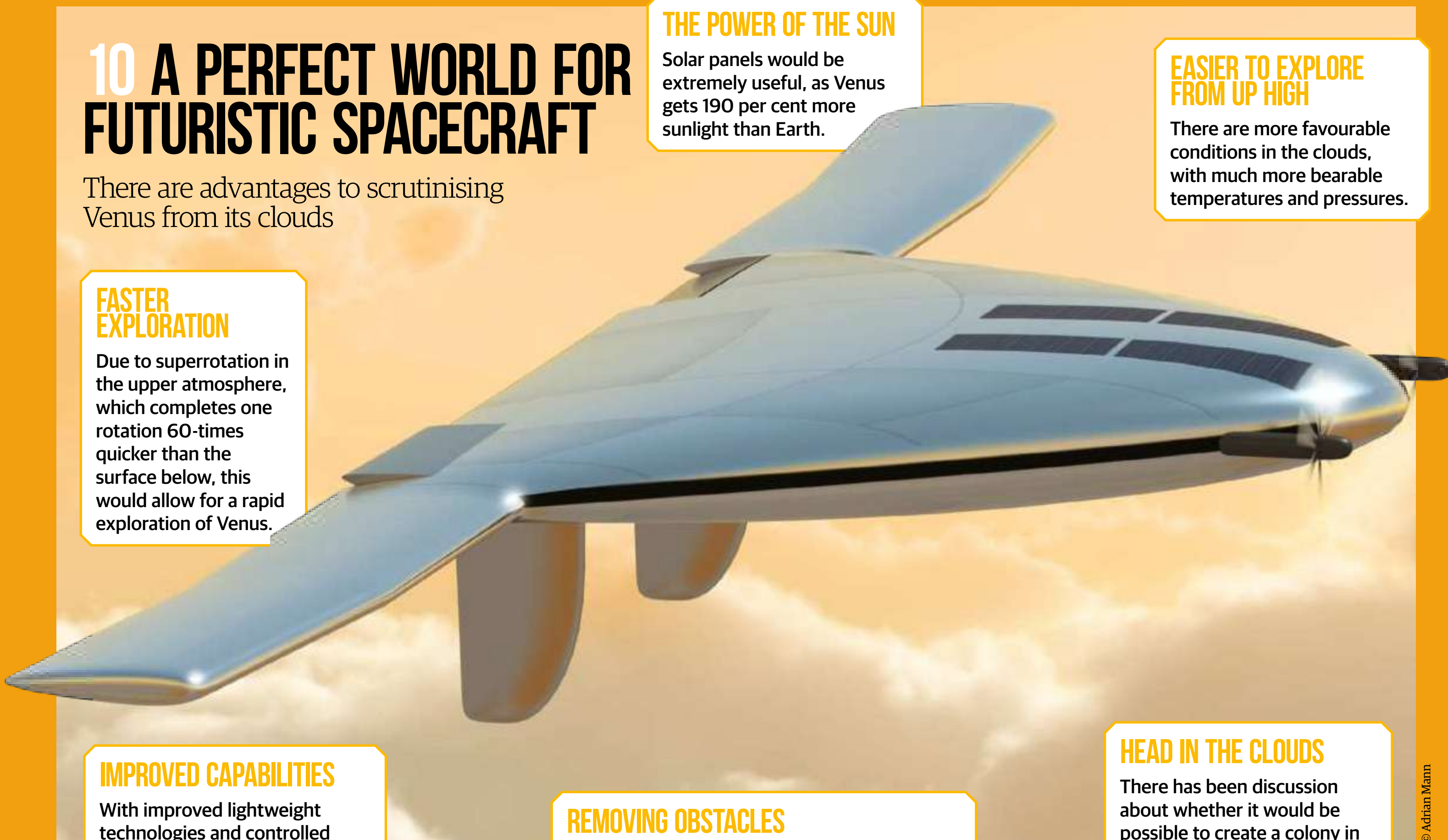
Based on past exploration missions, the surface of Venus contains rocks of different shades of grey, carving out valleys and giving birth to mountains, similar to Earth.

Volcanoes

Both planets contain at least 1,500 active and dormant volcanoes on the surface.

10 A PERFECT WORLD FOR FUTURISTIC SPACECRAFT

There are advantages to scrutinising Venus from its clouds



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THE POWER OF THE SUN
Solar panels would be extremely useful, as Venus gets 190 per cent more sunlight than Earth.

EASIER TO EXPLORE FROM UP HIGH
There are more favourable conditions in the clouds, with much more bearable temperatures and pressures.

FASTER EXPLORATION
Due to superrotation in the upper atmosphere, which completes one rotation 60-times quicker than the surface below, this would allow for a rapid exploration of Venus.

IMPROVED CAPABILITIES
With improved lightweight technologies and controlled aerial mobility, aircraft on Venus is now a more likely proposal than it was in the 1960s.

REMOVING OBSTACLES
In constant flight in the Venusian sky, this eliminates the need to navigate around harmful terrain and the planet's many volcanoes.

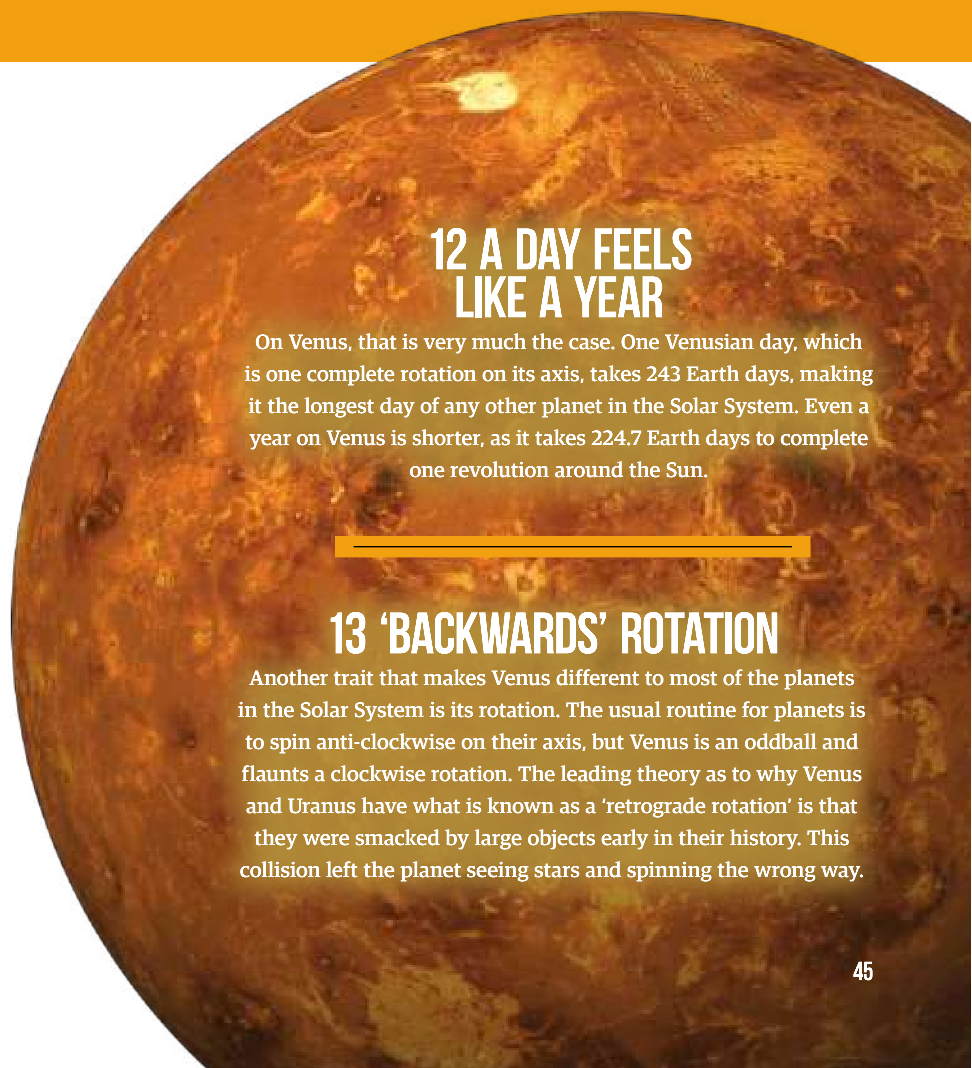
HEAD IN THE CLOUDS
There has been discussion about whether it would be possible to create a colony in the clouds of Venus, much like Cloud City on Bespin in the movie franchise *Star Wars*.

> "CONDITIONS ON VENUS THAT WOULD BE FAVOURABLE FOR LIFE COULD EXIST IN THE CLOUDS"

11 LIFE IN THE CLOUDS

Researchers have proposed that life could be found on Venus – just not on the surface. A study by Sanjay Limaye of the University of Wisconsin-Madison's Space Science and Engineering Center suggested that microbial life could be present in the cloud tops.

Microbial life on Earth has been found at altitudes of 41 kilometres (25 miles), and these researchers have said that conditions on Venus that would be favourable could exist at altitudes of 48 to 51 kilometres (30 to 32 miles). Here, temperatures would be roughly 60 degrees Celsius (140 degrees Fahrenheit) and pressures would be similar to Earth at sea level.



12 A DAY FEELS LIKE A YEAR

On Venus, that is very much the case. One Venusian day, which is one complete rotation on its axis, takes 243 Earth days, making it the longest day of any other planet in the Solar System. Even a year on Venus is shorter, as it takes 224.7 Earth days to complete one revolution around the Sun.

13 'BACKWARDS' ROTATION

Another trait that makes Venus different to most of the planets in the Solar System is its rotation. The usual routine for planets is to spin anti-clockwise on their axis, but Venus is an oddball and flaunts a clockwise rotation. The leading theory as to why Venus and Uranus have what is known as a 'retrograde rotation' is that they were smacked by large objects early in their history. This collision left the planet seeing stars and spinning the wrong way.

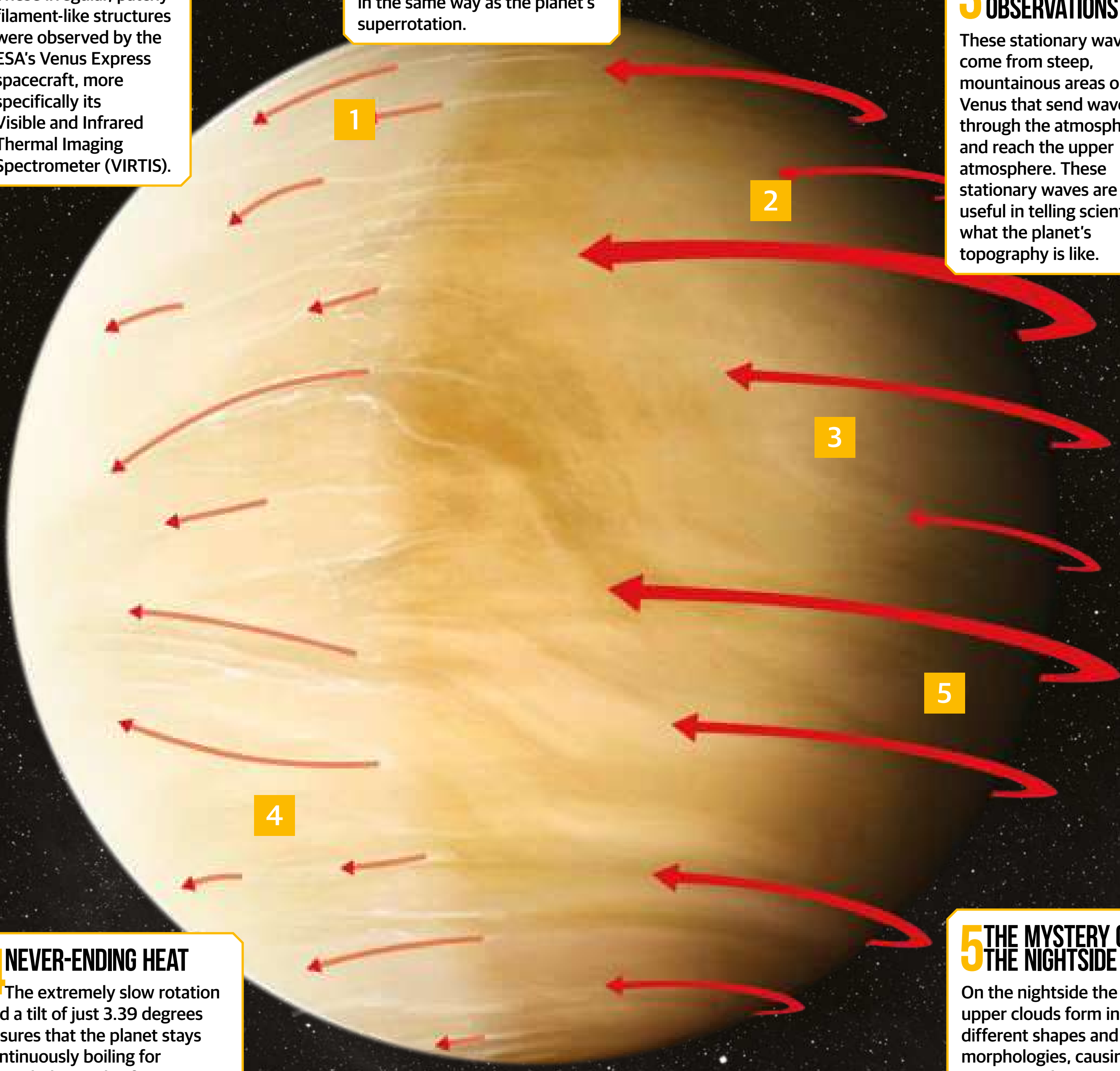
14 WHAT THE FUTURE HOLDS

Researchers want to understand every planet in the Solar System. Efforts in the late-20th century showed that Venus is a difficult planet to observe remotely from the surface, but with new technologies and a better understanding comes innovative exploration ideas. A lot of these new ideas have a common theme, which is exploring Venus from within the clouds. As Venus has more favourable conditions in the clouds, with wind speeds that allow an object to travel around the planet much faster than it rotates, scientists are looking to introduce aircraft or airships. By utilising solar and wind power, and the added help of buoyancy, robotic missions could become a feature of Venus in the foreseeable future.

15 REWINDING THE CLOCK

Venus wasn't much different from Earth once upon a time, and could have even supported life. 700 million years ago, Venus suffered dramatic changes in its climate that saw it bulk up its atmosphere in a process known as a 'runaway greenhouse effect'.

Before the runaway greenhouse effect took over, it is believed that Venus had a reasonable atmosphere and could have harboured liquid water for about 2 or 3 billion years. Before carbon dioxide dominated the atmosphere and made it too hot and dense, it is possible that Venus had an environment that could have supported life for billions of years.



1 SEEN FROM ABOVE

These irregular, patchy filament-like structures were observed by the ESA's Venus Express spacecraft, more specifically its Visible and Infrared Thermal Imaging Spectrometer (VIRTIS).

2 STATIONARY WAVES

Scientists have found stationary waves, or 'gravity waves', in the nightside's atmosphere that do not move in the same way as the planet's superrotation.

3 INDIRECT SURFACE OBSERVATIONS

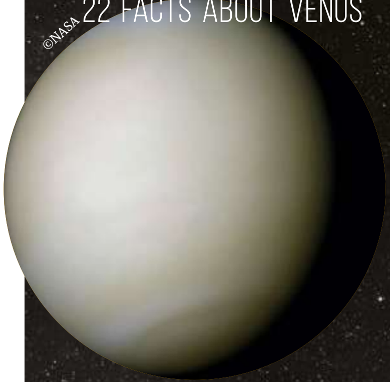
These stationary waves come from steep, mountainous areas on Venus that send waves through the atmosphere and reach the upper atmosphere. These stationary waves are useful in telling scientists what the planet's topography is like.

4 NEVER-ENDING HEAT

The extremely slow rotation and a tilt of just 3.39 degrees ensures that the planet stays continuously boiling for extended periods of time.

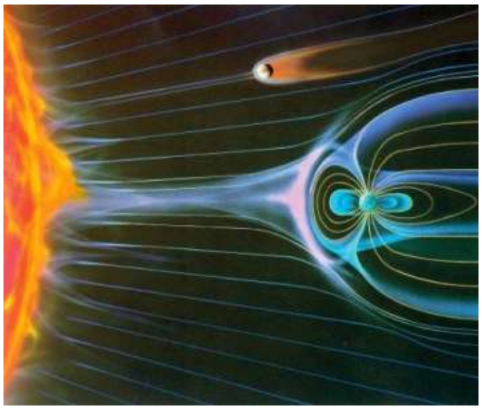
5 THE MYSTERY OF THE NIGHTSIDE

On the nightside the upper clouds form into different shapes and morphologies, causing a more irregular system.



16 LOSS OF A MAGNETIC FEELING

Although it is often referred to as Earth's twin, something that differentiates the two planets deep down to their cores is that Venus creates a negligible magnetic field. Planetary scientists believe that Venus has an iron core that is a similar size to Earth's. However, due to the sluggish rotation of Venus, consequently reducing the motion of the planet's core, this weakens the planet's magnetic field, or magnetosphere.



17 IT HAS HAD MANY SPACECRAFT VISITORS

Before attention turned to the exploration of Mars and other planets in the Solar System, Venus was the target that space agencies wanted to send their robotic missions to. This genesis of interplanetary exploration began with a lot of spacecraft and launch failures, starting with the Soviet Union's Tyazhely Sputnik in February 1961.

The first craft to aim for Venus experienced a launch failure, and there have since been 41 other missions launched with the intention to explore the planet. Of these missions, over 20 have been successful, and the first of these to conduct a successful planetary encounter was NASA's Mariner 2 space probe on 14 December 1962.

18 CASE OF THE MISSING LIGHTNING

There are electrical pulses bursting through the heavy atmosphere, but the missions that have gone to Venus to find them have made it an even more confusing endeavour. Ground-based telescopes and space probes – including NASA's Cassini, the European Space Agency's Venus Express and the Japan Aerospace Exploration Agency's (JAXA) Akatsuki missions – have had nothing more than some subtle hints about the presence of Venusian lightning. Researchers believe it could still be present, but it is just much more localised and more rare, which is why there has been no definitive evidence yet. Or it could be the case that there isn't lightning at all.

19 SOVIET SUCCESS AT VENUS

The Russian Space Agency, Roscosmos, is not particularly well known for its robotic exploration missions in recent years, as its missions are now few and far between. Before the dissolution of the Soviet Union in 1991, the country was prominent in Venus exploration missions in the 1970s and 1980s. One historic mission that the Soviets conducted was Venera 7 in December 1970, which became the first mission to land on a different planet. Then, in March 1982, the Venera 13 lander managed to survive Venus' extreme temperatures and pressures for over an astonishing two hours.

20 ONE OF THE BRIGHTEST IN THE SKY

Because Venus is in such close proximity to Earth, it is the third-brightest celestial object in the night sky, sitting behind the Sun and the Moon. The Latin nickname for Venus, which is largely unused in modern days, is 'Lucifer', which translates to 'light bringer'. Lucifer is also a name for the Devil, which is quite a coincidence considering the hellish conditions on the surface of Venus.

21 A SOURCE OF SHADOWS

Because Venus is the third-brightest object in the night sky, it is bright enough to cast shadows on the surface of Earth. Only two other celestial objects are capable of this: the Sun and the Moon. However, very good eyesight is needed to see these Venusian shadows.

22 VENUS' WEIRD WINDS

Although the planet moves slowly, the clouds move across the atmosphere once every four Earth days; this is known as 'superrotation'. This generates speeds of 360 kilometres (224 miles) per hour, which surpasses the speeds of the most dangerous hurricanes on Earth. The speeds decrease with cloud height, creating winds that are just a few miles per hour on the surface.

PLANET PROFILE EARTH

The rocky world that we call home is full of wonders

A rather pretty blue-and-white planet orbiting an otherwise obscure G-type main sequence star, Earth is notable largely for being the only place in the universe to have evolved organic life. Other than this quirk of chemistry, the third planet from the Sun also has active plate tectonics, and it's one of the few planets whose moon fits perfectly over its Sun during an eclipse, leading to some fantastic sights. It is the densest planet in its Solar System, and the largest of the four rocky planets closest to its star. An atmosphere 100 kilometres (62 miles) thick coats the planet, offering it protection from ultraviolet light given out by its nearest star thanks to its layer of ozone. Heating of the upper atmosphere means it's slowly losing its hydrogen and helium into space, but at a very slow rate.

With its thick atmosphere and yellow sunlight, much of Earth's vegetation is green, though most of its inhabitants are not. Its position at around 150 million kilometres (93 million miles) from its star means liquid water is commonplace on its surface – both salty and non-salty forms, freezing at the poles – though a recent increase in atmospheric carbon dioxide levels is causing this ice to melt. Unlike its neighbour Mars, which is populated solely by robots, biological life flourishes both in Earth's oceans and on the third of the planet not covered with water.

An axial tilt of 23.5 degrees leads to seasons on the planet, which combine with both atmospheric and oceanic circulations to produce a variety of weather types, some of them extreme. A single, large natural satellite is tidally locked to the planet, and its gravitational pull affects the water level beneath it, causing tides. Along with the many artificial satellites created by its inhabitants, Earth also has a small number of quasi-satellites, mostly captured asteroids circulating around Lagrange points L4 and L5 in horseshoe orbits.

Earth is currently 20,000 years into an interglacial period, part of a cycle of ice ages that sees glaciers coat large parts of the planet over periods of up to 500,000 years. The current interglacial should end in around 25,000 years, though warming caused by increased atmospheric carbon dioxide levels could delay this by trapping heat within the atmosphere.

In a billion years' time, the energy received by Earth from its star will have increased by ten per cent, enough for the oceans to be lost thanks to a combination of subduction into the planet's mantle and photodissociation of the water molecules by increased levels of ultraviolet light. Without surface water, plate tectonics will come to a halt. Earth will become similar to its near-twin Venus, its neighbour on the sunward side, with a runaway greenhouse effect eventually raising the surface temperature to 1,330 degrees Celsius (2,426 degrees Fahrenheit).

In another 5 billion years, the Sun will run out of hydrogen to burn in its core and will begin the process of swelling into a red giant. As it expands, Earth, along with Venus and the small rocky planet Mercury, will be engulfed by its chromosphere. Tidal forces will break up the Moon, briefly turning it into a ring system before the surface and mantle are stripped from the Earth, leaving only its core. The final legacy of Earth will be an increase in the Sun's metal content of 0.01 per cent.

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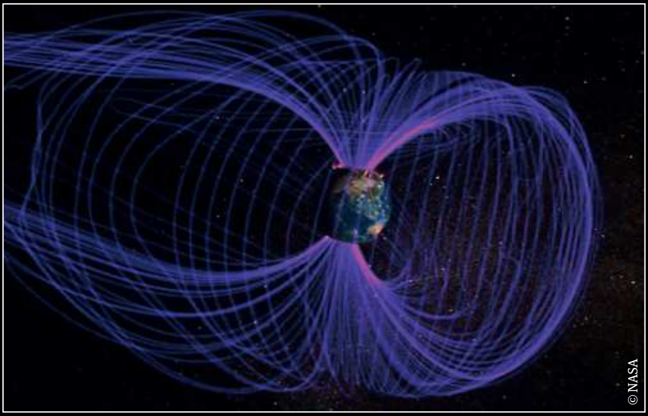

© NASA

Left: Earth is surrounded by a magnetic bubble called its magnetosphere

"WITH ITS THICK ATMOSPHERE AND YELLOW SUNLIGHT, MUCH OF EARTH'S VEGETATION IS GREEN"

COMPOSITION

32.1%
IRON

30.1%
OXYGEN

15.1%
SILICON

13.9%
MAGNESIUM

2.9%
SULPHUR

1.8%
NICKEL

1.5%
CALCIUM

1.4%
ALUMINIUM

1.2%
TRACES OF OTHER ELEMENTS

NEWS FROM EARTH

EXTINCTION EVENT

A study published in the journal *Biological Conservation* suggests that 84 per cent of animals and plants in mountain regions risk being wiped out if the temperature rises by more than an average of three degrees Celsius (5.4 degrees Fahrenheit), with this rising to 100 per cent on islands.

Geographically unique species such as Madagascar's lemurs and the snow leopards of the Himalayas are 2.7 times more likely to go extinct than species that are more widespread. More than 60 per cent of unique tropical species are likely to go extinct thanks to the action of climate change alone, and places such as the Caribbean islands and Sri Lanka could lose most of their endemic plants by 2050. Up to 92 per cent of species on land and 95 per cent of those in the sea could face negative consequences.

The researchers – from Brazil, Norway and South Africa, among others – concluded that if the world can keep global average temperature rises within the terms of the Paris Climate Agreement, then the risk to vulnerable species drops by a factor of ten. With a 1.5 degrees Celsius (2.7 degrees Fahrenheit) rise, only two per cent of land and marine species face extinction.


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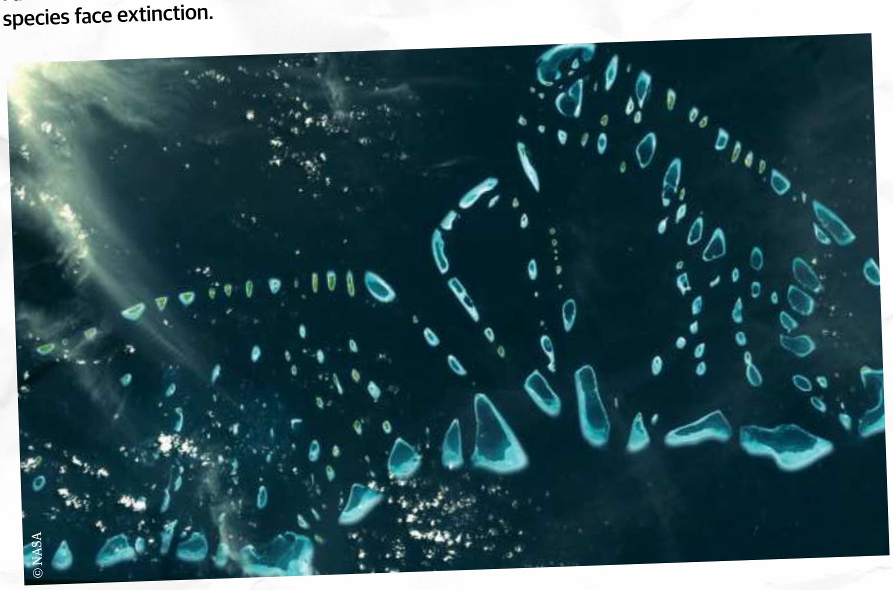
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ARTIFICIAL ISLAND

Not content with all the islands already available to it, the dominant mammal species on Earth has been busy making more. A new artificial island near Malé, the capital of the Republic of Maldives, an archipelago in the Indian Ocean, will act as a refuge for people stranded by rising sea levels. With more than 80 per cent of its 1,190 islands just one metre (3.2 feet) above the water, the Maldives has the lowest terrain of any country in the world, which makes it particularly susceptible to sea-level rise. Construction of the new island, known as Hulhumalé, began in 1997, and it has grown to over four square kilometres (1.5 square miles) in area. It sits two metres (6.5 feet) above sea level, constructed from sand pumped on top of submerged coral, and is now the fourth-largest island in the archipelago.

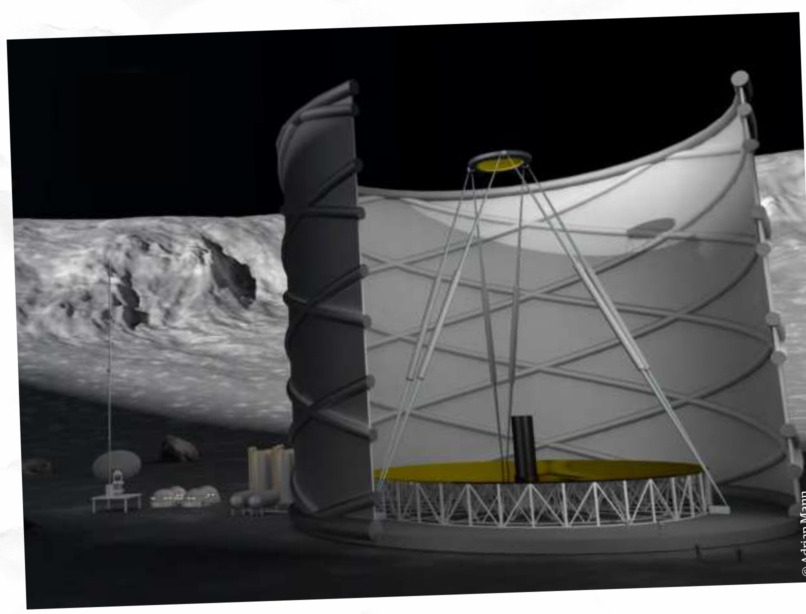
With sea levels predicted to rise by up to half a metre by 2100 even if the Paris Climate Agreement targets are hit, land reclamation projects like this may become more common as populations are driven from low-lying areas.

MOON TELESCOPE

An early stage proposal has received funding from NASA to build a radio telescope in a crater on the far side of the Moon. Similar in concept to the Arecibo Observatory, the Lunar Crater Radio Telescope would take advantage of the Moon's many meteor craters to support its structure.

Because of the way Earth and the Moon are tidally locked, one side of the Moon always faces away from us. The advantage of building such a device on the Moon, particularly on its far side, is the shielding effect it gives against Earth-generated noise and even the radio waves emitted by the Sun. It would also be able to observe the universe at frequencies that are blocked by Earth's atmosphere, such as those below 30MHz. Observations in these wavebands have never been made by humans.

The proposal is to deploy two wall-climbing robots in a crater three to five kilometres (1.8 to 3.1 miles) in diameter. The robots would then weave a dish one kilometre (0.62 miles) across using a wire mesh. A receiver would then be suspended above this dish on two crossed cables, each end held by a robot that would be able to move, adjusting the position of the receiver for the best results.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SURFACE WATER AND OCEAN TOPOGRAPHY MISSION

Due to launch in April 2022, SWOT – a joint development between NASA and French space agency CNES, with help from Canada and the UK – is designed to accurately measure the height of Earth's surface water. The SWOT mission aims to measure how bodies of water change over time. It will use a radar altimeter to measure the height of oceans, rivers and lakes across 90 per cent of the globe at least twice every 21 days at an average precision better than 1.5 centimetres (0.6 inches).

This data will lead to better weather and climate forecasting, providing more accurate information about sea and river levels that can be plugged into the supercomputer prediction models used by meteorological agencies. It will also be able to measure the 3D shape of floodwater, track flood levels and improve our ability to predict future floods.

The largest effect SWOT may have on Earth's population is the data it will provide about freshwater management. This will help urban planners to manage the distribution of water for agricultural, industrial and urban needs by providing information about reservoirs and major rivers. The enhanced knowledge we will gain of Earth's water cycle and ocean circulations will help us to better understand everything from surface water to the deep oceans, and this should improve our reactions to natural disasters, waterborne diseases, sharing water sources among different populations and countries, as well as managing electricity production from renewable means and safeguarding biodiversity.

Below: Artist's model of the SWOT spacecraft

© NASA © Getty

PLANET EARTH BY NUMBERS

43KM
The difference in the Earth's diameter at the equator than if measured pole-to-pole

ONE NATURAL SATELLITE

ONE ATMOSPHERE
Mean surface pressure

14°C
Average surface temperature

1G
Average surface gravity

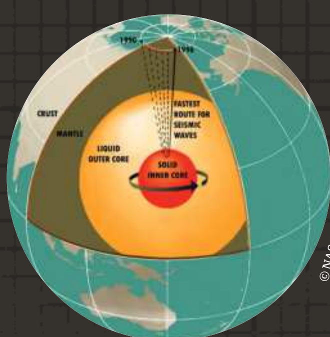
5,430°C
Temperature at inner core

1AU
Average distance to Sun

THE EVOLUTION OF PLANET EARTH

- **Date:** 4.54 billion years ago
  Activity: Earth formed from a protoplanetary disc around a young star.
- **Date:** 4.5 billion years ago
  Activity: Dense elements sank to the centre, forming Earth's core, while the outside layer cooled and solidified.
- **Date:** 4.48 billion years ago
  Activity: A massive impact with another body sent a portion of Earth's crust into orbit, forming the Moon.
- **Date:** 4.4 billion years ago
  Activity: Volcanism released water vapour into Earth's atmosphere, raining down to begin the formation of oceans.
- **Date:** 3.5 billion years ago
  Activity: Earth's magnetic field was established, with a magnetosphere about half the modern radius.
- **Date:** 750 million years ago
  Activity: The earliest known supercontinent, Rodinia, began to break apart.
- **Date:** 180 million years ago
  Activity: The most recent supercontinent, Pangaea, broke apart.
- **Date:** 65 million years ago
  Activity: Formation of the Himalayas began as the Indian subcontinent drifted into Asia.
- **Date:** 6 million years ago
  Activity: A small African ape began a family tree that led to a dominant species.

Below: The structure of the Earth from the surface crust down to the solid inner core



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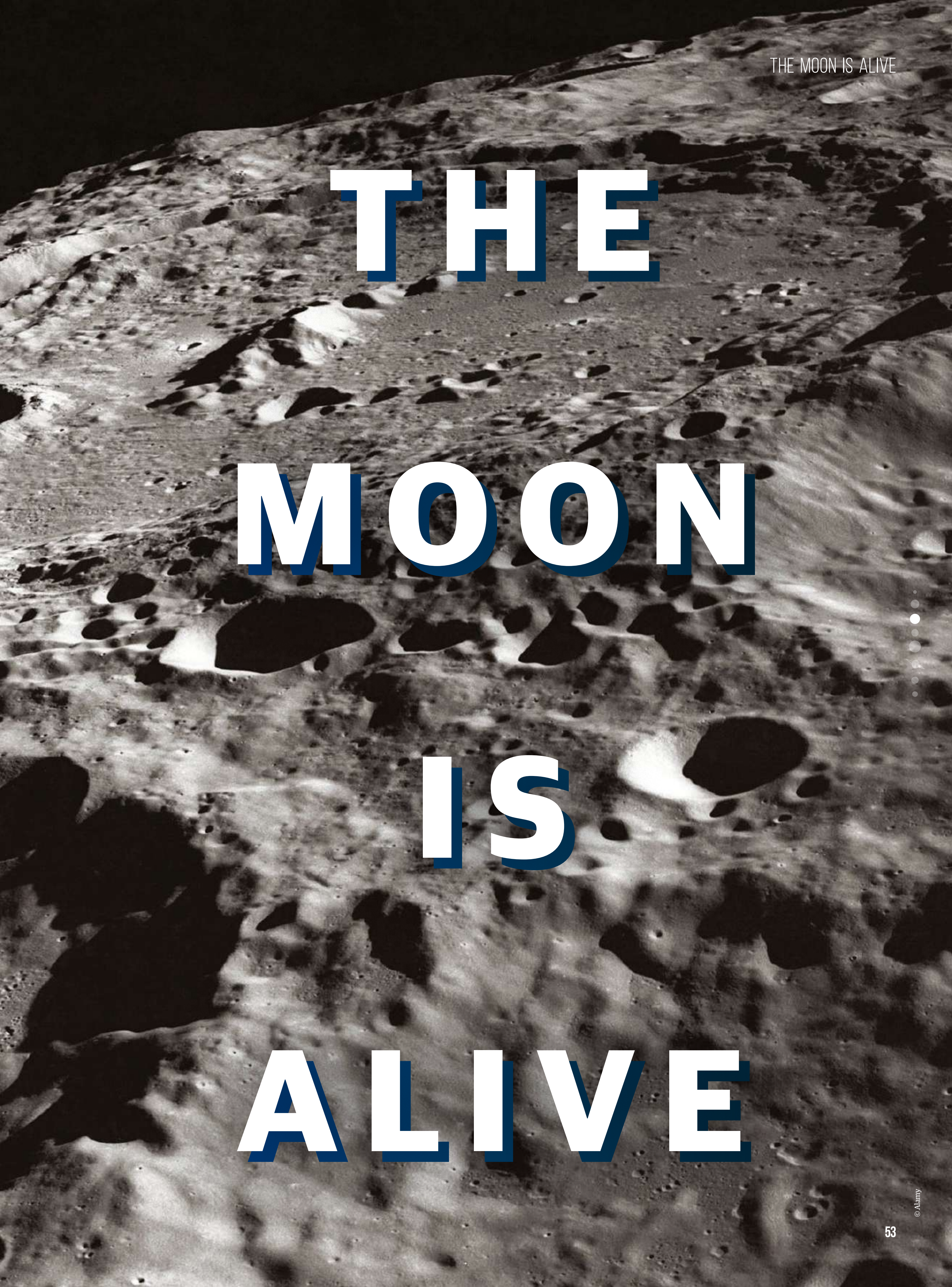
THE LUNAR SURFACE IS HOME TO MORE ACTIVITY THAN ITS BARREN APPEARANCE LETS ON

Reported by James Romero

THE MOON IS ALIVE



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From the 4-billion-year-old, 230-kilometre (143-mile) wide Clavius impact crater to Neil Armstrong's 50-year-old, size-nine-and-a-half 'one small step', the Moon has recorded momentous episodes across much of our Solar System's history.

For scientists its surface provides a 4-billion-year-old astronomical archive of events that shaped both its own peppered surface and our planet too. A passive observer, its record-keeping value lies in the fact that things tend to happen to it, rather than it showing signs of its own activity.

And yet it seems we might have missed something. Something small in size but larger in significance. Located right between the eyes of the 'Man in the Moon', some scientists believe they have found evidence that lunar volcanoes were erupting when dinosaurs roamed the Earth – and perhaps they are still erupting somewhere on the surface right now. If confirmed such activity would tear up current models of the Moon's internal structure and how it evolved, as well as rewriting assumptions about other supposedly 'lifeless' worlds beyond. As missions are proposed to visit this intriguing site, we ask, is the Moon still alive?

A quick glance of its ancient, battered surface offers little hope. The Moon's cratered appearance is in stark contrast to not only the planet it orbits, but also many local, smooth-surfaced planets, dwarf planets and moons. In each case the main concealer of these impact blemishes is volcanism. This recycling of surface crust is familiar to us on Earth, but also accounts for the lack of cratering on Venus, Jupiter's moon Io and even further out to Pluto.

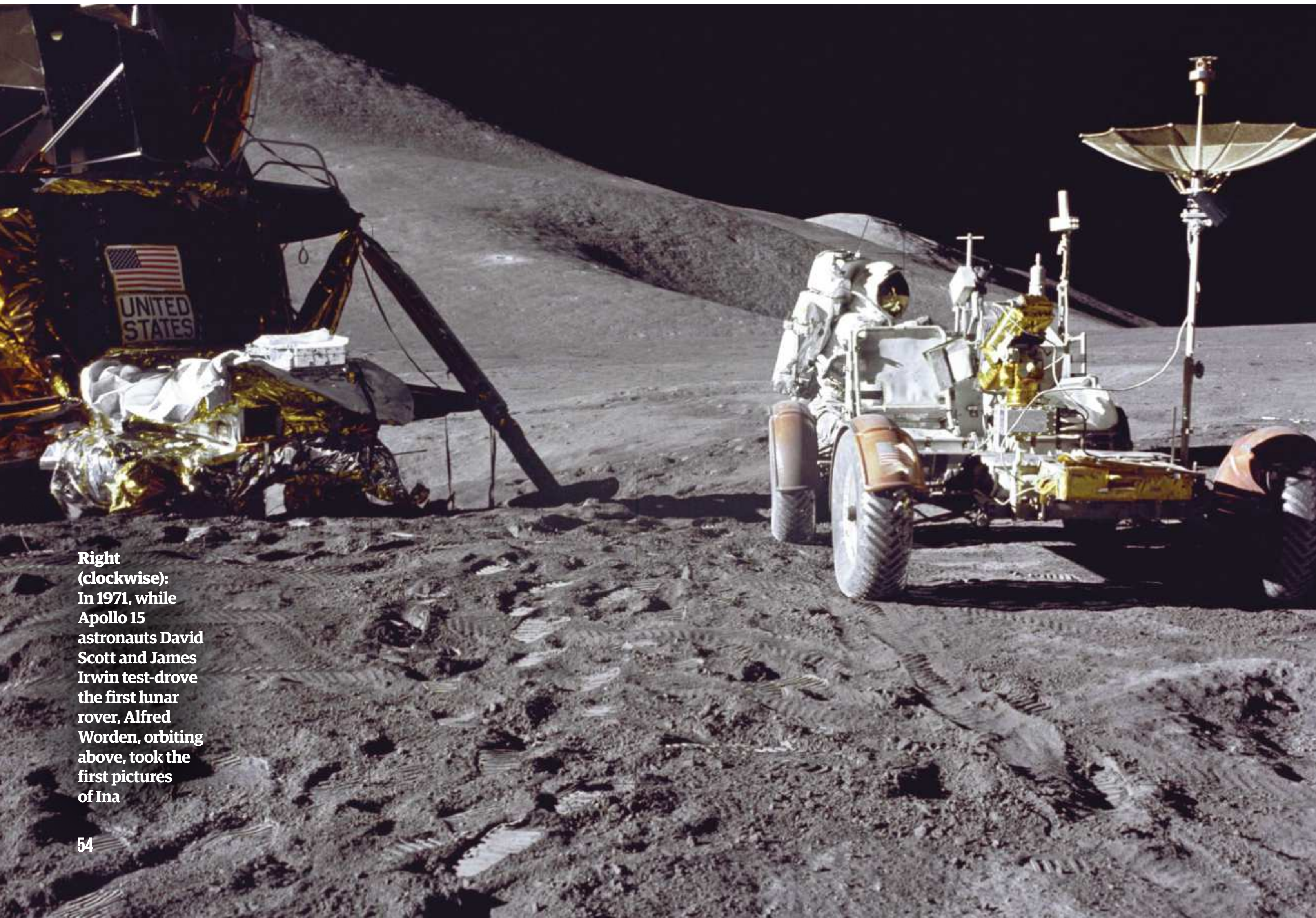
But no such rejuvenation appears to have played out on the lunar surface for a while. While the large, dark mares covered some of the most ancient cratered crust with wide-scale eruptions, billions of years of exposure to Solar System violence has left them sporting plenty of blemishes of their own. The concentration of such cratering dates the mares to between 3 and 4 billion years old, figures backed up by analysis of recovered lunar rock samples. And after that? Well, not much. "We thought that volcanism had ended by 1 billion years ago," says Julie Stopar, a director at the Lunar and Planetary Institute in Houston.

This made sense. The Moon, as a relatively small body, shouldn't have ever had huge amounts of internal heat. And what it had should have been lost quickly due to the large surface area to mass ratio that blights smaller worlds.

This heat might have another effect. Evidence from thrust faults shows the lunar surface shrunk as it cooled, contracting the crust up against itself. This makes it even more difficult to imagine volcanic activity piercing through. But then came a photograph that put that all in doubt.

In 1971, while Apollo 15 astronauts David Scott and James Irwin test-drove the first rover on the lunar surface, Command Module pilot Alfred Worden, orbiting above, took a picture of a strange blotchy feature. Named Ina, it was an exposure of a dynamic landscape – by lunar standards anyway. The Moon's surface is a collection of homogeneously flat vistas covered by broken-up

"IT IS HARD TO EXPLAIN HOW YOU CAN HAVE YOUNG VOLCANISM BASED ON EVERYTHING WE KNOW ABOUT THE MOON" JULIE STOPAR



Right (clockwise): In 1971, while Apollo 15 astronauts David Scott and James Irwin test-drove the first lunar rover, Alfred Worden, orbiting above, took the first pictures of Ina

rock and dusty regolith. It's a landscape bombarded into uniform consistency, where any notable topography has been eroded through landslides and impacts over vast eons of time.

Ina is different. It comprises steep, 20-metre (65-foot), smooth-sided mounds surrounded by lower relief, rougher deposits. Like drops of "dirty mercury" on the lunar surface was how astronomer Ewen Whitaker described the mounds, which are typically less than a few hundred meters across. However, with 45-degree slopes, they represent some of the steepest deposits on the Moon. It would be quite a sight. "It will look even more dramatic than even a fresh impact crater," says Stopar. "The rough materials around it will look a bit like a rough sea around the smooth island mounds."

The unusually well-preserved deposits and lack of superposed impact craters led to suggestions Ina was formed by volcanic eruptions during the last 100 million years - possibly gaseous basaltic lava flows surrounded by ashy pyroclastic deposits. "Metre-scale topography cannot survive for long, geologically speaking, due to the constant sandblasting of micro-meteoroid and macro-meteoroid bombardment," says Mark Robinson, a lunar researcher at NASA.

"It certainly looks much younger than anything else on the surface bar the youngest impact craters," observes Stopar. But this was a significant claim at the time, and has been a cause of much debate ever since. "It would totally destroy our current understanding of the thermal history of the Moon," says Lionel Wilson, planetary scientist at Lancaster University and sceptic of the young volcanism hypothesis.

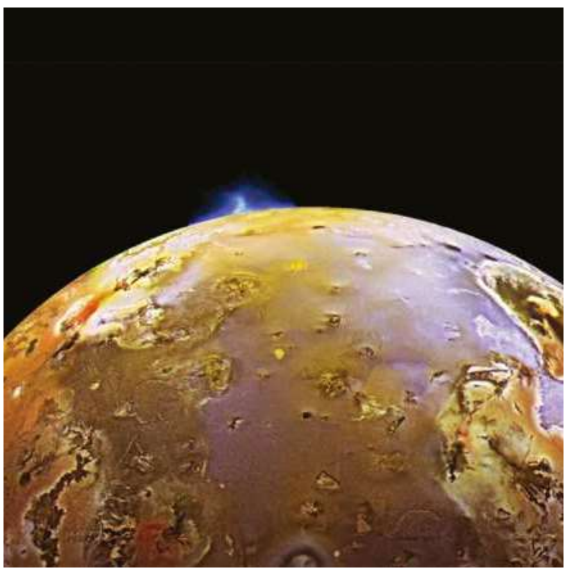
Wilson isn't alone in his hesitance, especially after higher resolution imaging by the Lunar Reconnaissance Orbiter (LRO). In 2012 NASA's Brent Garry argued the lack of crisp fractures, often associated with young volcanic deposits due to the surface cooling quicker than the interior, implies either they eroded over billions of years, or never formed, and therefore Ina was not volcanic. For modellers of the Moon's evolution it is a tempting conclusion. Dismissing the young volcanism hypothesis certainly makes for a better fit with everything we know about our celestial companion.

However, no matter how logical it was to ignore, the suggestion that in Ina we are looking at evidence of a planetary body that is still alive, or at least was very recently, won't go away.

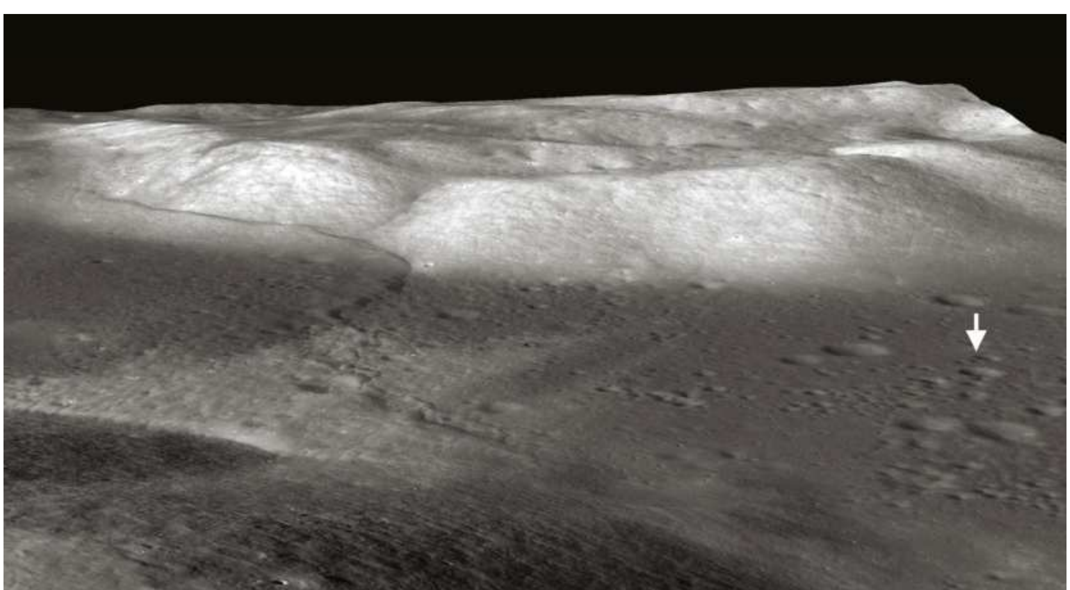
"It is really hard to explain how you can have young volcanism based on everything we know about the Moon. However, others say we can't possibly preserve these features for 3 billion years, so it has to be young," says Stopar. And if Ina was proving hard to explain, the Lunar Reconnaissance Orbiter found 70 similar-looking sites, collectively known as Irregular Mare Patches, or IMPs. And for some IMPs, the evidence for youth might be stronger still.

"There is one IMP located on the ejecta of the Aristarchus crater. This is a young crater that we think is roughly 200 million years old," says Stopar. So we have near-pristine Ina, IMPs seemingly superimposed on crater material only a few hundred million years old, plus a collection of 70 other features for ongoing monitoring. Surely we can allow ourselves to imagine lava spewing out somewhere on the lunar surface today? "It's not much of a stretch," agrees Robinson.

With such a tantalising prospect at stake - not to mention our entire theoretical basis for the structure and evolution of the Moon - a resolution between observation and simulation was required. Theories to account for the ill-fitting Ina and its IMP friends have fallen into two categories: those maintaining Ina is old have given it a facelift. In 2006 Peter H. Schultz at Brown University proposed a spring clean via later subsurface outgassing that removed the overlying regolith, while Le Qiao,



As the most volcanically active body in the Solar System, Jupiter's moon Io has a very young, uncratered surface



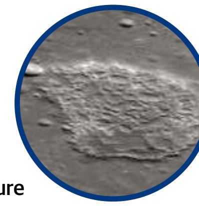
Thrust up lunar cliffs is evidence of the Moon's contraction as it cooled. Some have questioned where such compression forces would allow lava to reach the surface

All photos © NASA

HOW DO WE KNOW THAT THE MOON IS ALIVE?

There are increasing signs of ongoing life

FINDING INA

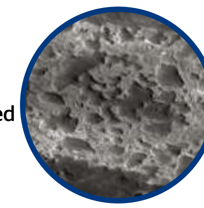


In 1971 as part of Apollo 15, Alfred Worden took a picture of a strange, blotchy feature. Later named Ina, the exposure represented a uniquely dynamic landscape.

LIKE LIQUID DROPS OF MERCURY

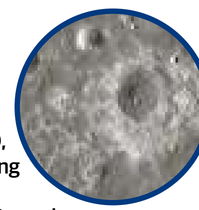
Against a lunar landscape of almost continuous flat vistas covered in a layer of broken-up rock and dusty regolith, Ina's smooth, steep-sided mounds stand out.

PRISTINE INA



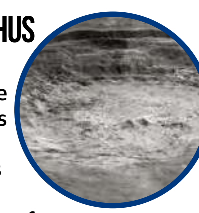
Ina's unusually well-preserved deposits and lack of superposed impact craters led to suggestions it must be no older than 100 million years old – very recent compared to the lunar surface.

IMP SPECULATION



In 2014 a team from Arizona State University, analysing data from NASA's LRO, found 70 similar-looking sites to Ina, which are collectively known as Irregular Mare Patches.

PATCHY ARISTARCHUS



One IMP is located on top of the ejecta of the Aristarchus crater. This fresh crater is itself only 200 million years old, providing further evidence this new class of lunar features are young.

IMP CONCENTRATION

Grouping of IMP sites in one region might provide additional support for young volcanism by reducing the amount of internal heat the Moon needs to have retained to power them.

WATER ON THE MOON

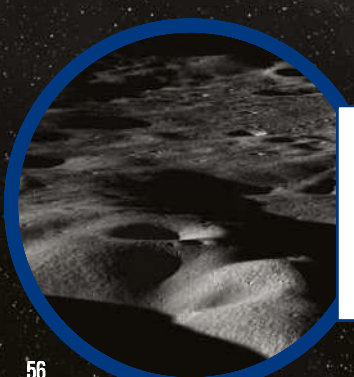
Ideas of a bone-dry lunar surface have been overturned by detection of water within rock minerals, and as surface ice

1 FRA MAURO HIGHLANDS

The samples collected from the Apollo 14 landing site were in 2008 found to include minerals containing water in the form of hydroxyl, a chemical that includes hydrogen and oxygen.

2 BULLIALDUS CRATER

In 2013 a team at John Hopkins University analysing spectroscopic data from the Moon Mineralogy Mapper detected magmatic water in the central peak of this impact crater.



3 SOUTHERN POLES

In 2009 a rocket from NASA's Lunar Crater Observation and Sensing Satellite spacecraft deliberately crashed into the shadowed crater Cabeus. Within the material thrown up, 150 kilograms of

© ESA

4 SHACKLETON CRATER

Perpetually in shadow, the crater provides a cold trap to freeze water from comet impacts. The Lunar Prospector spacecraft revealed higher than normal amounts of hydrogen, indicative of water ice.

SPACECRAFT

CHANDRAYAAN-1

The first Indian lunar probe spent almost a year in orbit. It contained the Moon Mineralogy Mapper imaging spectrometer instrument that provided the first high-resolution spatial and spectral map of the entire lunar surface.

LUNAR CRATER OBSERVATION AND SENSING SATELLITE

Launched after the first detection of water by Chandrayaan-1, LCROSS was envisioned as a low-cost means of determining the nature of hydrogen detected at the polar regions of the Moon.

NASA'S CLEMENTINE

Clementine found early evidence of water ice after scanning the surface with radar in 1996. However, follow-up observations with radio telescopes suggested the spots surveyed had too much Sun exposure for ice to survive.

LUNAR PROSPECTOR

The 19-month mission was designed for a low-polar orbit investigation of the Moon. This included mapping the surface composition and locating lunar resources, measuring magnetic and gravity fields and studying outgassing events.

5 TAURUS–LITTROW VALLEY

As well as water within minerals from the lunar interior, the Apollo samples, like those from Apollo 17, reveal water inside crustal rocks, thought to be evidence of younger volcanic intrusions.

6 ROZHDESTVENSKIY CRATER

In 2018 a Hawaiian team found evidence of surface-exposed water ice within reflectance spectra of indirect lighting from the crater's permanently shadowed regions.

7 DESCARTES HIGHLANDS

Modern analysis of various lunar samples, including those from this Apollo 16 site, have revealed water inside apatite minerals of the lava plains that arise deep within the Moon.

> "A LOT OF THE PATCHES ARE FOUND IN AREAS WHERE WE THINK VOLCANISM COULD HAVE LASTED THE LONGEST"
>
> JULIE STOPAR

visiting Brown, suggested a recent collapse into a subsurface void.

Wilson was involved in a 2017 paper advocating the replacement of standard mare basalt lava with a more exotic variety that degrades differently, creating the illusion of youth. Their lava of choice is a gas-rich magmatic foam, like an extreme pumice. While critics have questioned how such a fragile deposit could survive billions of years of micrometeorite impacts, Wilson believes his solution could link IMPs to the origin of the mare basalts themselves. "Maybe IMPs are places where there were vents? During the very last stage of the mare eruptions, it [the lava] is not flooding out any more. The bulk of the gas comes out in intermittent explosions and gas-filled lavas."

On the other side are those trying to keep the Moon volcanically active long enough to account for eruptions in the last 100 million years. One way might be to ignore the vast majority of it. Most IMPs are located in the same area, along with elevated concentrations of thorium, a radioactive source of internal heating in subsurface rocks. "A lot of the patches are found in areas where we think volcanism could have lasted the longest. Perhaps as recently as 50 to 60 million years ago," suggests Stopar. And if the last vestiges of lunar internal heat had stuck around beneath certain parts of the surface, perhaps occasional upwellings might not have had such a tough job reaching the surface. This was one conclusion of earlier work, again involving Stopar, which challenged the locked-up

All photos © NASA

VOLCANOES ON THE MOON

The Moon has been volcanically active for most of its history

PRE-NECTARIAN PERIOD

Lunar crust formed via mineral crystallisation of a global magma ocean, forming the lunar highlands. With liquid surface volcanism not possible, hot vapour release did create an atmosphere, however.

EARLY IMBRIAN EPOCH

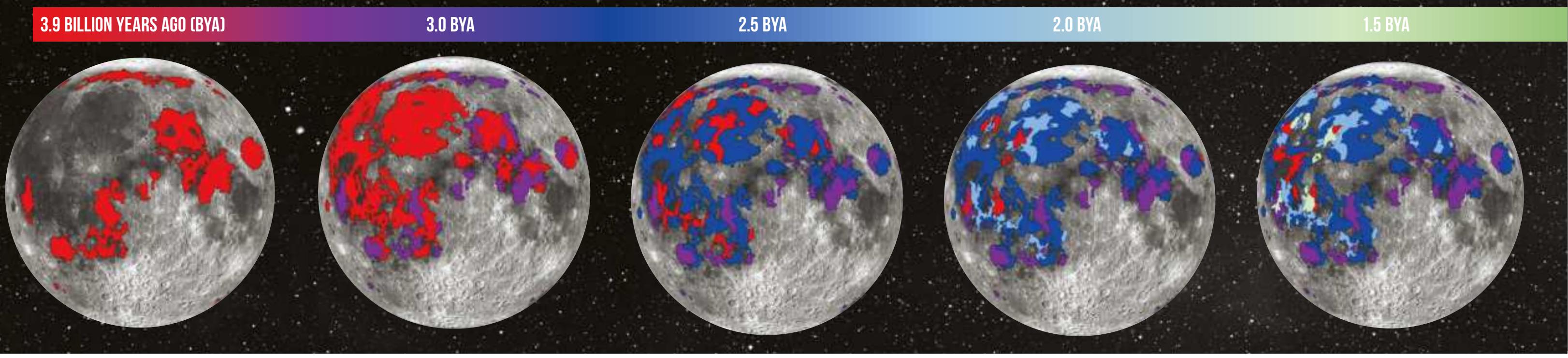
The mantle lying below the lunar basins melted due to frequent giant meteorite impacts that came with the late heavy bombardment and thinned

LATE IMBRIAN EPOCH

The thinned crust led to peak rates of effusive wide-ranging basalt eruptions, creating the famous mare, the dark, smooth lowlands of the Moon. There is also evidence of

ERATOSTHENIAN PERIOD

The massive basaltic volcanism of the Imbrian period tapered off and ceased. During this era late-stage volcanism filled low-lying regions in and around Mare Imbrium and



© NASA

surface hypothesis. "There are lots of young tectonic features on the Moon that suggest the crust is still moving around," she explains.

While Robinson sees Ina and the other IMPs as compelling evidence for lunar volcanism in the last few 100 million years, Stopar sees problems with both hypotheses, and Wilson is maintaining his scepticism. "The discussion can get quite heated," he says.

One way out of the impasse would be to visit an IMP, with Ina preferred due to its size and history of being studied. While the Lunar Reconnaissance Orbiter is providing the best-ever images of the surface, the evidence of collapse features or recent volcanism on the sub-metre scale is unlikely to be resolved. "We actually have to be there. It requires us looking into the soil on the landform. I don't think we can get that from orbit," argues Stopar.

But who is 'we'? In the same year US Vice President Mike Pence called on NASA to return American astronauts to the Moon by 2024, is Stopar suggesting setting up camp around the base of Ina and mounting its smooth slopes? Not exactly.

Putting a geologist on the Moon has benefits. There are many interesting sites where complex scientific questions could be chipped away. These include the south pole, where elevated concentrations of rare lunar water could explain our own blue planet. This is one reason the US has targeted it for a lunar base.

The Ina mystery is different. It represents a relatively straightforward puzzle where we think we know what we are looking for. The key indicators include the small fractures that Garry couldn't see from orbit, lava flow textures and collapse pits, as well as the general size, shape, porosity and mineralogical content of surface grains, which should all be indicative if derived from broken-up foamy lavas. In fact, so well defined is the question that Stopar and colleagues have offered to answer it for just $100 million, a knock-down price in planetary exploration.

For that money you get the Irregular Mare Patch Exploration Lander, or IMPEL, a SmallSat mission proposed this April in the journal *Planetary and Space Science*. The lander would carry a mast camera for high-resolution colour imaging of the landing site, and a microscopic imager for close-up analysis of the surface regolith and any signs of fracturing. "It's a great idea," says Wilson. "It's a fast

© Getty

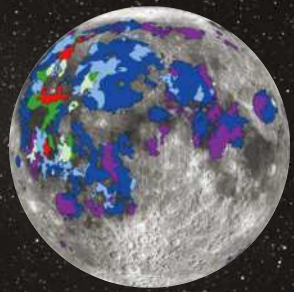
Above: Planetary scientist Julie Stopar has proposed a 'fast and cheap' SmallSat lander mission to visit Ina and look for signs of recent volcanism

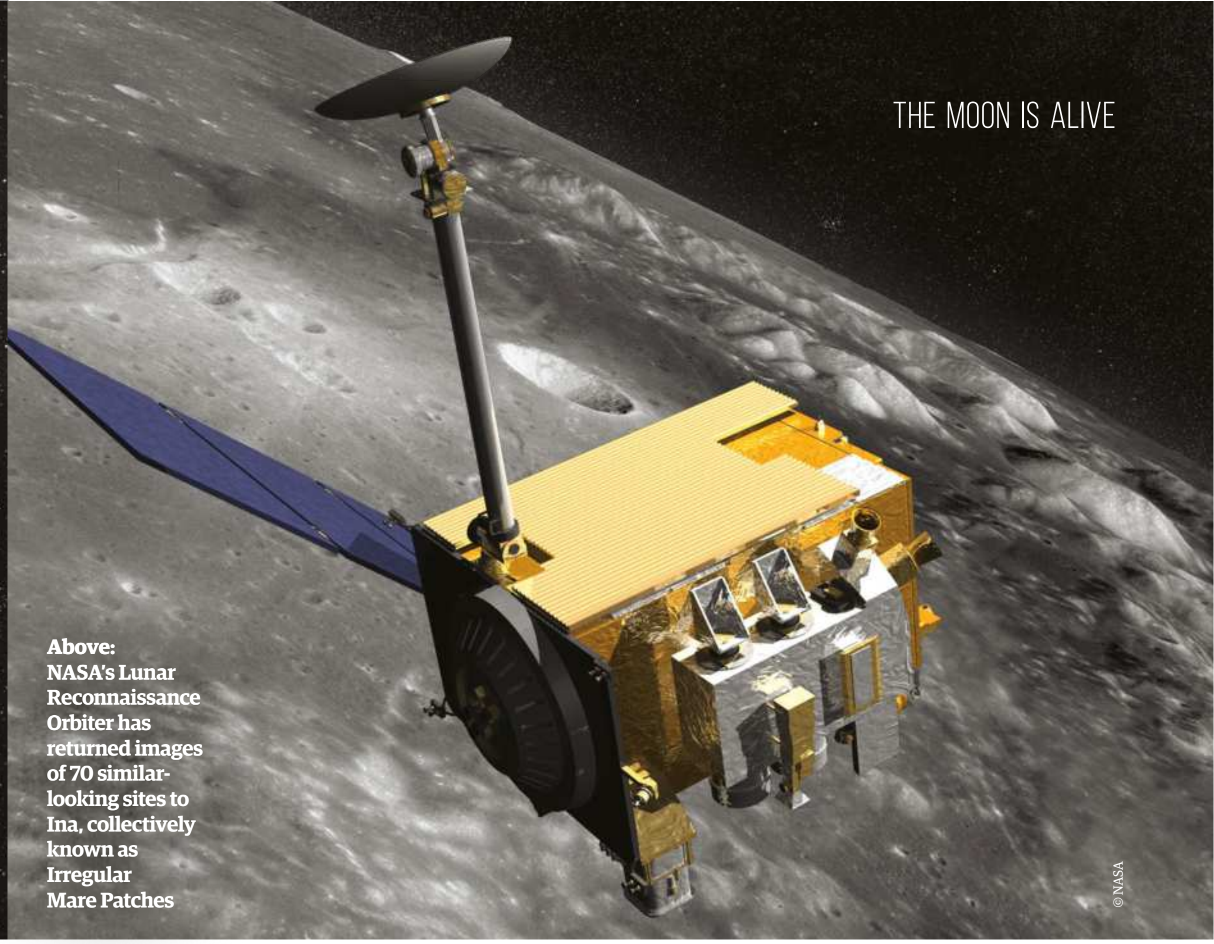
Left: The constant recycling of rock through plate tectonics and volcanism across Earth's history makes it a poor record of planetary and Solar System

COPERNICAN PERIOD

It is generally thought lunar volcanism had ceased by the Copernican period. However, evidence from Ina and 70 other similar-looking mare patches suggest small-scale volcanism may have continued.

1.0 BYA





Above: NASA's Lunar Reconnaissance Orbiter has returned images of 70 similar-looking sites to Ina, collectively known as Irregular Mare Patches

and cheap mission. And that is not a criticism."

However, while he sees the potential for great science, he doubts IMPEL alone can date Ina. "Detailed morphological studies by a lander would be enormously useful in establishing exactly what happened, but only radiometric dating will convince me of when." However, he still sees value in SmallSats to answer this question. In fact, Wilson suggests sending more. "Why not send five of these things to five candidate IMPs to establish the most interesting one, then send the larger mission to collect samples."

In the meantime the rest of the community is left with orbital images. Here there have been no signs of any structural changes that could indicate present-day activity. "It is still a leap to say it [the Moon] is still active today," states Stopar. "However this could be based on the limited timetable we have been observing."

"If any form of observation were to capture unambiguous images of any actual eruption, then of course I would accept that there is something fundamentally wrong with our current understanding of the Moon's interior – and relish trying to understand what we have been doing wrong all these years," says Wilson.

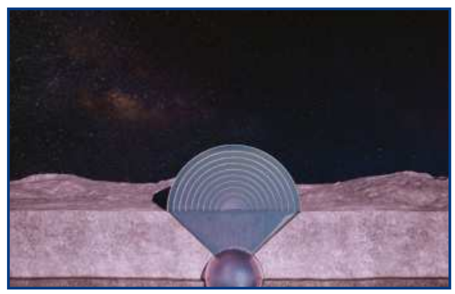
Stopar believes the implications of such a discovery might go well beyond the lunar interior. If the Moon could support recent volcanism, then we would need to re-examine assumptions about other small moons and dwarf planets. This includes whether the same mechanism for preserving residual heat could be keeping sub-surface water liquid elsewhere, maintaining more of the oceans known to exist within Jupiter's Europa and Saturn's Enceladus. "We need to go there to Ina because it is a place where we can answer a really important question with big implications, just based on this one small area," Stopar concludes.

THE MOON'S EXPLOSIVE OUTGASSING

Outbursts could explain the appearance of the lunar surface

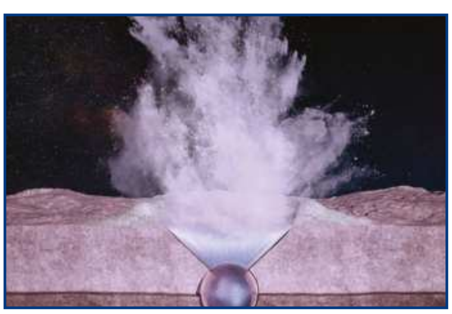
1 BUILDING UP OF GAS

Gas builds up between the lunar megaregolith and the upper layer of regolith (which has a low diffusivity). The pressure is built up by the gas, lifting a cone of material to the surface.



2 MIXTURE OF GAS AND MATERIAL

The concoction of regolith and gas now creates a substantial volume on the surface. It's filled with shells of regolith particles. The cloud of matter and gas expands.



3 MOON MATTER ESCAPES TO CRATER

The cloud continues to expand until it reaches a point where it's not very thick when viewed from above. Regolith that has fallen from the gas cloud piles up around the crater.

4 ALL GAS ESCAPES

All of the gas starts to leak out and any lunar material that was trapped within the cloud has managed to escape. It is deposited onto the ground around and inside the 'impact'.

PLANET PROFILE
MARS

The Red Planet has a host of new robots investigating it

Across the gulf of space, no other planet has fired humanity's imagination so much as the Red Planet, and it has frequently been associated with violence, war and death. To the ancient Sumerians it was Nergal, a god of war and plague who presided over the netherworld. In Mesopotamia it was the 'star of judgement of the fate of the dead'. The Chinese associated it with the element fire, while for the people of the Tiwi Islands off the coast of Australia the planet was one of the four wives of the Moon Man, who followed the path of the Sun Woman through the sky – the other wives were Mercury, Jupiter and Venus. The planet was a familiar sight to the astronomers of ancient Egypt, Babylonia, Rome – where Mars was the god of war – and Greece, where Aristotle noticed that the planet vanished behind the Moon during an occultation, proving it was farther away.

Following the invention of the telescope in the 17th century, Mars could be observed in greater detail, and Christiaan Huygens was able to observe Syrtis Major – which he thought was a plain, but we now know to be a volcano – the first surface feature seen on another planet, in 1659. He was also able to measure Mars' day length as 24 hours and 30 minutes – only seven minutes short of the true value.

It would be another 312 years before a human-made spacecraft would touch down on Martian soil, with the Soviet Union's Mars 3 lasting 110 seconds on the surface and managing to transmit only part of a single image that showed no detail. There would be several more failures until NASA's Viking 1 touched down in 1976 and operated for over six years.

Exploration of the planet has continued, and right now there are three operational rovers on its surface. Curiosity and Perseverance are from the US, while Zhurong hails from China. These missions are the lucky ones. There have been a spate of failed missions from the USSR, US, UK and Japan – from rocket failures and solar panels failing to open to a mix-up between the units of measurement used in America and the metric system used by most of the rest of the world, which caused NASA's Mars Climate Orbiter to either burn up or skip off the Martian atmosphere and into deep space in 1999.

Human missions to Mars have been a dream since the earliest days of space exploration. In 2004 the Vision for Space Exploration announced by US president George W. Bush called for a crewed mission to the Moon in 2020 as a stepping stone to Mars. In 2007 NASA administrator Michael D. Griffin said the agency aimed to put a person on Mars by 2037. The Journey to Mars plan, formulated by NASA in 2015, uses the ISS and an asteroid captured in 2020 to test deep-space habitation facilities. That phase is behind schedule, but the ISS phase is underway and set to last until 2024. Humans on Mars in the 2030s is still NASA's goal.

Left: Mars Pathfinder explores the rocky surface of the Red Planet

Above: Mars' north pole, taken by the Mars Global Surveyor

Below: Mars Global Surveyor image of ice at the south pole

ATMOSPHERIC COMPOSITION

95%
CARBON DIOXIDE

2.6%
MOLECULAR NITROGEN

1.9%
ARGON

0.16%
MOLECULAR OXYGEN

0.06%
CARBON MONOXIDE

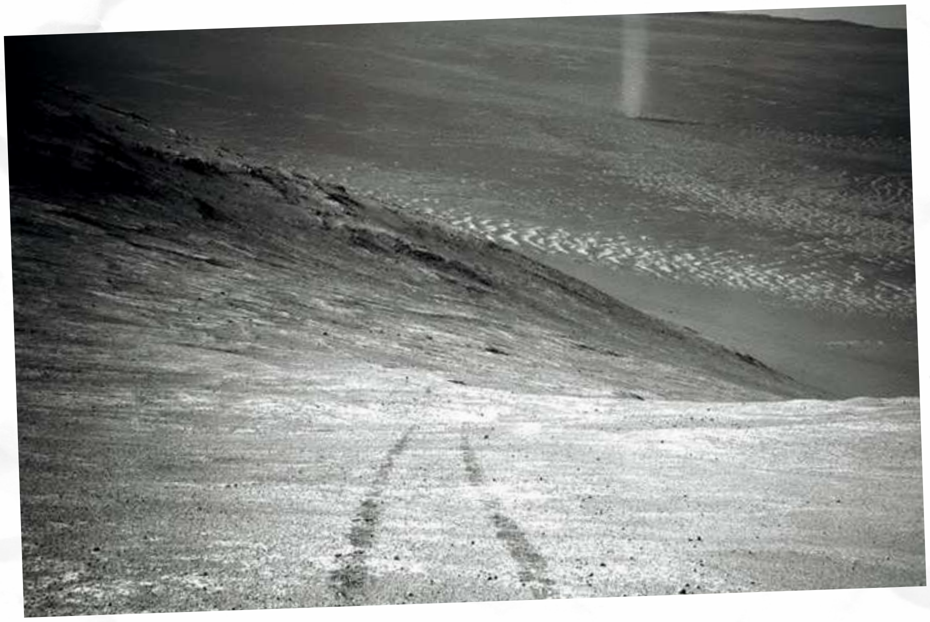
0.03%
WATER VAPOUR

NEWS FROM MARS

RENEWABLE ENERGY ON MARS

Renewable power is a little bit tricky on Mars, which is farther from the Sun, has dust storms and has no tides. What it does have, however, is wind, and so scientists from Delft University of Technology have come up with the excellent idea of designing robots to fly huge power-generating kites in the Martian atmosphere. "Despite the low density of the Martian atmosphere, wind speeds are high enough to make wind energy competitive with nuclear power in terms of power produced per unit mass," the scientists wrote in a research paper. One kite could generate 127 megawatt-hours of energy per year, the scientists say, enough to power five households in the US.

The assembly, which will also have solar panels – though Mars gets only 43 per cent of the sunlight we enjoy on Earth – will catch the wind and be reeled out, performing a series of tacking manoeuvres to maximise its speed and pulling force. This is all controlled by a robot that steers the wing-like kite, changing its angle of attack. Once the cable is pulled out, the kite can be dropped to minimise the pull as it's reeled back in, ready to fly again.



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OXYGEN ON MARS

The atmosphere on Mars is thin and not conducive to effective human breathing. It's a hostile environment, and any astronauts who explore there will need to take their own oxygen. If humans are to build an outpost on the planet, however, they need a way of generating their own oxygen, which is also a critical component of rocket fuel. NASA estimates that to get four astronauts back from Mars would take about 25 tonnes of the gas.

Enter the Mars Oxygen In-Situ Resource Utilization Experiment (MOXIE), carried aboard NASA's Perseverance rover. This uses 300 watts of power to heat carbon dioxide from the Martian atmosphere, where it strips the oxygen atoms away from the carbon and sends the resulting carbon monoxide back outside. During its first test in April, it created just over five grams of oxygen in an hour, which is about ten minutes of breathing for an astronaut. MOXIE is just a demonstrator, but larger, more powerful versions of it could one day produce enough oxygen for a colony.

INGENUITY WOBBLES, BUT FLIES ON

The small robotic helicopter carried by NASA's Perseverance rover made its sixth flight across the Martian surface near the end of May, but it was a flight marked by control disruptions and power spikes.

The helicopter was asked to climb to ten metres (33 feet) above the surface before flying to the west to take stereoscopic images of a region of interest there. It had been flying for 54 seconds when a glitch was noticed in the stream of images coming from the navigation camera. Only one image was lost, but this led to the following images being delivered with inaccurate timestamps. Ingenuity uses an algorithm to navigate that uses both visual data about where things are and timestamps to tell it when it saw them.

As a result, Ingenuity began adjusting its velocity and tilting back and forth in an oscillating pattern, and this behaviour persisted for the rest of the flight. It encountered roll and pitch excursions of more than 20 degrees, large control corrections and spikes in power consumption. Despite this, the robotic aircraft was able to land within five metres (16.5 feet) of its intended location.

© NASA

NUCLEAR ROCKETS

All this talk of oxygen and energy is all well and good, but before you can start deploying these technologies on Mars you've got to get there. NASA has explored the Solar System using a range of chemical rockets and gas-fuelled manoeuvring systems, but is investigating two methods of nuclear propulsion to speed humanity to the Red Planet.

The first is nuclear electric propulsion, otherwise known as the ion drive, which supplies low thrust over a long interval to gradually build high acceleration. The other is nuclear thermal propulsion, which provides high thrust and twice the propellant efficiency of chemical rockets. NASA is looking into preliminary reactor design concepts for such a rocket, which heats a fluid, usually liquid hydrogen, in a nuclear reactor. Once it reaches a high enough temperature, the fluid expands through a rocket nozzle to create thrust.

Nuclear thermal propulsion has been on NASA's radar for more than 60 years. Research on the subject once concentrated on fission reactors, but these came with a number of problems, notably that no one wanted a flying fission reactor with even a chance of exploding over their heads. Recent research has moved to nuclear fusion power, and such a rocket could be constructed in orbit as an additional safety measure. Nuclear propulsion could enable missions to Mars at times when the planet is not favourably positioned relative to Earth, and could cut the round trip time of a crewed mission to just two years.

Above: Illustration of a Mars transit habitat and nuclear propulsion system that could one day take astronauts to Mars

MARS BY NUMBERS

15%
Mars is 15 per cent of Earth's volume

8 METERS
There is eight metres of permanent frozen CO_2 at the south pole

38%
Its gravity is 38 per cent of Earth's

70%
The polar caps are 70 per cent water ice

OLYMPUS MONS
The tallest mountain of any planet, it's 2.5 times the height of Everest above sea level

11%
Mars has 11 per cent of Earth's mass

7.7
Its soil pH is 7.7, which is slightly alkaline

Left: Olympus Mons is a dormant shield volcano, the biggest in the Solar System

EVOLUTION OF THE RED PLANET

- **Date:** 4.57 billion years ago
  Activity: Mars was part of the same protoplanetary disc as the other planets, swirling around the nascent Sun.
- **Date:** 4 billion years ago
  Activity: The Late Heavy Bombardment scarred Mars' surface – these craters can still be seen today.
- **Date:** 4 billion years ago
  Activity: Mars was hit by a body the size of Pluto, creating the smooth Borealis Basin that covers 40 per cent of Mars.
- **Date:** 3.8 billion years ago
  Activity: Substantial amounts of liquid water on the surface began to dry up due to the loss of the planet's magnetic field and its atmosphere.
- **Date:** 3.3 billion years ago
  Activity: Olympus Mons, a huge volcano, formed as part of a period of enormous geological activity.
- **Date:** 237 years ago
  Activity: Astronomer William Herschel declared Mars would offer "a situation in many respects similar to ours".
- **Date:** 144 years ago
  Activity: Asaph Hall discovered Phobos and Deimos, the Martian moons.
- **Date:** 50 years ago
  Activity: Humans started dropping craft and robots onto the surface, but many of these fail.

MARTIAN MOONS EXPLORATION

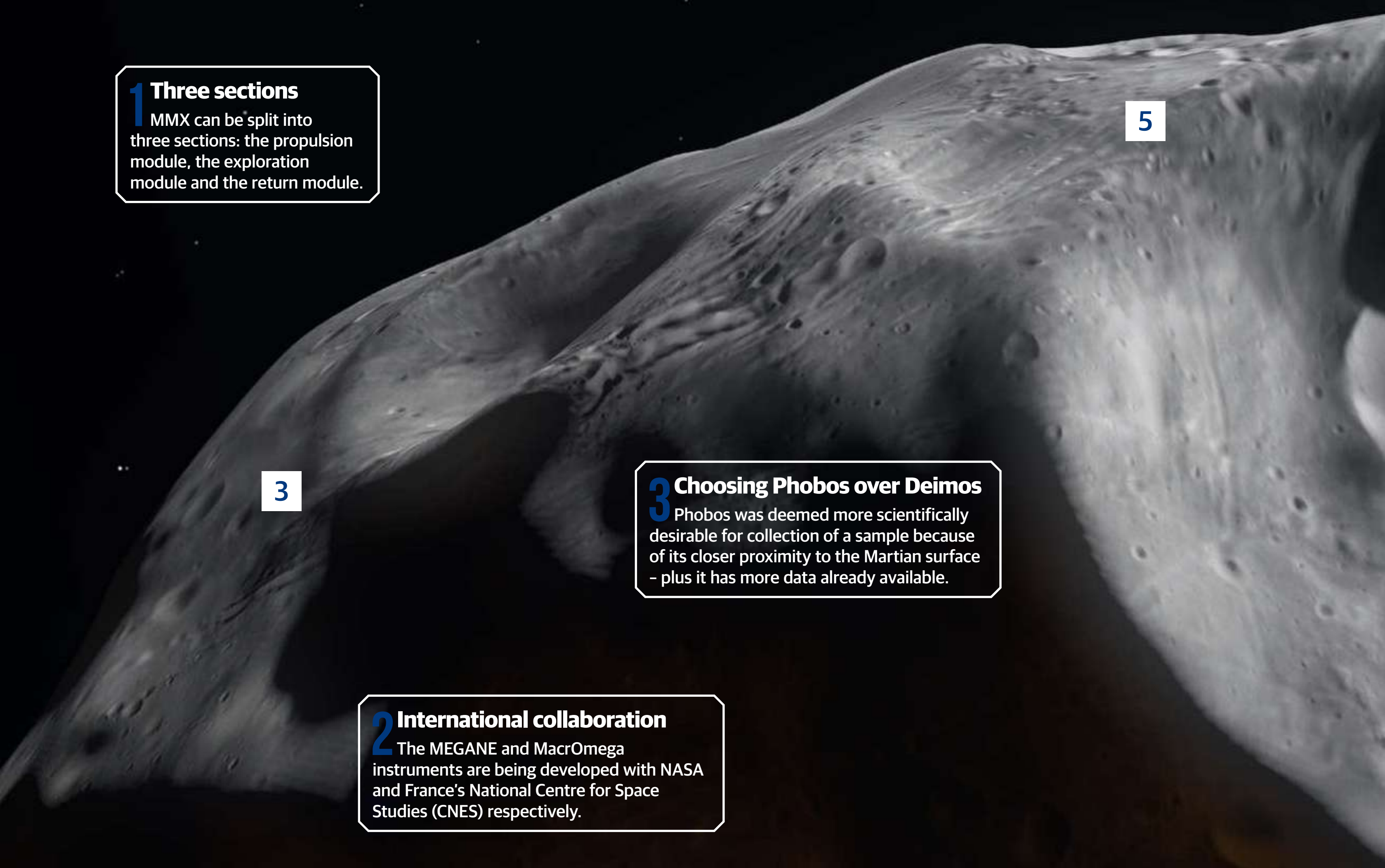
Japan's next sample-collection feat will be to the second and third closest natural satellites in the Solar System

Japan has a very adept space agency in terms of exploration. The Japan Aerospace Exploration Agency, or JAXA, has engineered the launches of the Hayabusa missions to near-Earth asteroids and the Akatsuki space probe to Venus. Although the Hayabusa2 spacecraft is the only mission so far to occur without a hiccup, there is much to learn from these mistakes, and JAXA is now readying itself to launch a new mission to Mars' moons, Phobos and Deimos.

JAXA is currently preparing its Martian Moons Exploration (MMX) mission, with a plan to launch towards Phobos and Deimos in 2024, gain scientific data from both objects upon arrival in 2025, collect a sample of Phobos in the process and finish the mission by returning the sample to Earth by 2029. Russia's space agency, Roscosmos, attempted the same feat in 2011 with the Fobos-Grunt mission. However, untimely rocket burns meant it did not reach a trajectory toward Mars, but instead became stranded in low-Earth orbit, ending with a controlled re-entry into the Pacific Ocean.

The main aim of the MMX mission is to investigate the origins of these two moons. Astronomers have never been able to truly understand the origins of Phobos and Deimos, which are 23 and 12 kilometres (14 and 7.5 miles) in diameter respectively. There are two leading theories as to how they formed. The first is that they are captured asteroids from the nearby asteroid belt. If this turns out to be correct, this could mean they may have transported water, volatiles or other organic compounds from further regions of the Solar System.

The second explanation is that they were formed after a huge collision involving the Red Planet, implying that these moons are essentially



1 Three sections
MMX can be split into three sections: the propulsion module, the exploration module and the return module.

3 Choosing Phobos over Deimos
Phobos was deemed more scientifically desirable for collection of a sample because of its closer proximity to the Martian surface – plus it has more data already available.

2 International collaboration
The MEGANE and MacrOmega instruments are being developed with NASA and France's National Centre for Space Studies (CNES) respectively.

frozen time capsules leftover from the planet's formation currently suspended in orbit, and could reveal a lot about the planet's past.

The new spacecraft will be well equipped with an instrumental suite capable of providing an extensive remote investigation of the moons' surfaces. This high-tech instrumental suite will consist of a gamma-ray and neutron spectrometer (MEGANE), a wide-angle multiband camera, a near-infrared spectrometer (MacrOmega) and several other cameras, sensors and spectrometers. But the centrepiece of the spacecraft will be its sample-collection suite.

JAXA is aiming to take what it has learnt from Hayabusa2 – which is currently on its way back to Earth carrying a sample of the asteroid Ryugu – and enhance it. Hayabusa2 was designed to collect a small sample of just 0.1 grams (0.004 ounces), but the MMX team need the spacecraft to gather a minimum sample of ten grams (0.4 ounces). The MMX sample-collection suite literally needs to be a hundred times better. There is no doubt that this call for technological improvement will be answered as this exploration mission develops.

On 19 February 2020 the MMX team announced that the mission has shifted from the pre-project phase into the development phase. This exciting news means that the team can begin working on the spacecraft's hardware and software and preparing the craft for launch. "In order to transition from a JAXA pre-project to project," stated the team on the official mission website, "the MMX mission team had to consider factors such as the importance of the scientific goals, the success criteria, the implementation system, the financial plan, schedule and identify risks and countermeasures."

4 Asteroids or ancient Martian rock?
Astronomers want to determine if these moons are asteroids caught by Martian gravity and pulled into orbit or ancient ejecta and debris leftover from a huge collision which has coalesced to form an orbiting body. The results for each of the moons could be different.

"ASTRONOMERS HAVE NEVER BEEN ABLE TO TRULY UNDERSTAND THE ORIGINS OF PHOBOS AND DEIMOS"

5 A long time coming
JAXA first began pondering the feasibility of a sample-return mission to Phobos in 2015.

© Adrian Mann

Instant expert

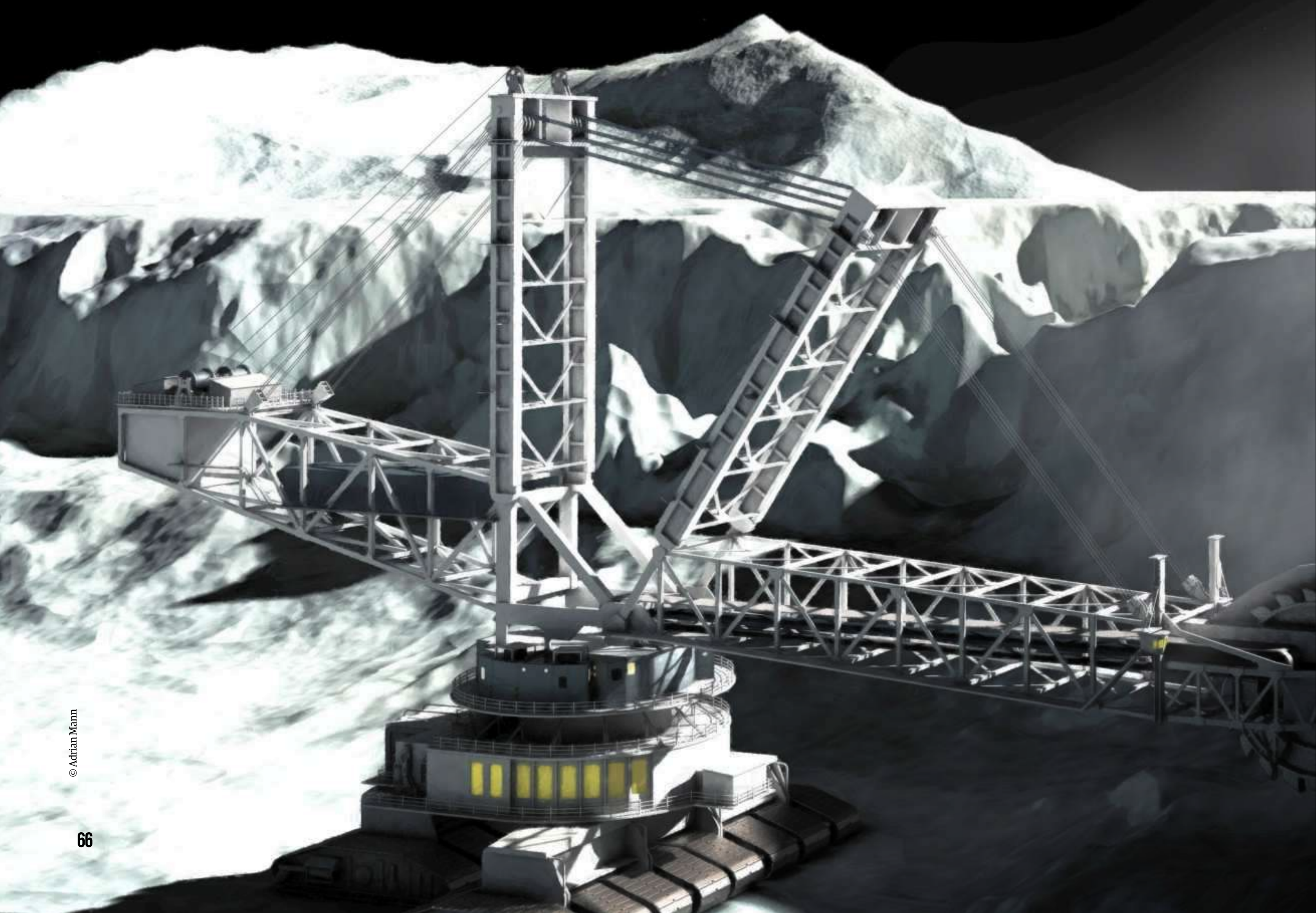
WHAT CAN WE DO WITH A CAPTURED ASTEROID?

Asteroids could provide us with rare resources

Asteroids have more than enough gold, plus other precious metals, to provide a few lifetimes' worth of fortunes. But there are plenty of other reasons asteroids are valuable. But how do we get these metals from these faraway asteroids? Perhaps the best way is to bring the space rocks to Earth. Most of the metals we use in our everyday lives are buried deep within the Earth. And we mean deep: when our young planet was still molten, almost all of the heavy metals sank to the core, which is pretty hard to get to. The accessible veins of gold, zinc, platinum and other valuable metals instead came from later asteroid impacts on Earth's surface.

Those asteroids are the fragmented remains of almost-planets, but they contain all the same mixtures of elements as their larger planetary cousins – and you don't have to dig down into their cores to get it. But the main problem with asteroids is that they are far away. To launch from Earth's surface and go into orbit, a rocket needs to change its velocity from zero to eight kilometres (five miles) per second. To rendezvous with an average asteroid, the rocket has to change its velocity by another 5.5 kilometres (3.4 miles) per second. That requires almost as much fuel as the launch itself, which the rocket would have to carry as dead weight, adding to the already-high cost of trying to set up a remote mining operation in the first place. And once the asteroid was mined, asteroid prospectors would be faced with a difficult choice: They could try to refine the ore right there on the asteroid, which would entail setting up an entire refining facility, or ship the raw ore back to Earth, with all the waste that would involve.

AR SCAN HERE



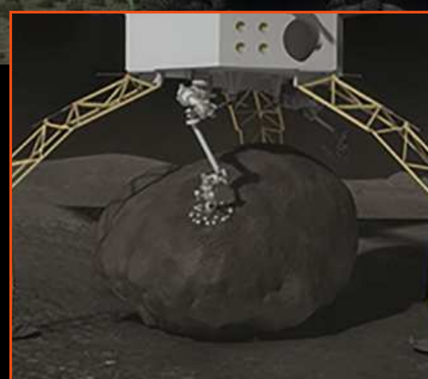
© Adrian Mann

BRINGING HOME THE GOODS

Instead of trying to mine a distant asteroid, how about we bring the asteroid to Earth? NASA's ill-fated Asteroid Redirect Mission (ARM) was an attempt to do just that. The goal of the mission was to grab a four-metre (13-foot) boulder from a nearby asteroid and return it to cislunar space – between the orbits of Earth and the Moon – where we could then study it at our leisure. To move the boulder, ARM would use solar electric propulsion, with solar panels absorbing sunlight and converting it into electricity. That electricity would power an ion engine. It wouldn't be fast, but it would be efficient – and it would eventually get the job done. Unfortunately, in 2017, NASA cancelled ARM. Some of the critical technologies wound up in other projects, like the OSIRIS-REx mission to the asteroid Bennu, and NASA continues to investigate and use ion engines.

WITHIN ARMS REACH

A recent study found a dozen potential asteroids, ranging from 2 to 20 metres (6.6 to 66 feet) across, that could be brought into near-Earth orbit with a change in velocity of less than 500 metres (1,640 feet) per second. The solar electric propulsion schemes cooked up for ARM would be perfectly capable of that, although it would take a while. Once an asteroid is in near-Earth space, many of the difficulties of asteroid mining are significantly reduced. A cislunar asteroid would be much easier to study and much easier to test different mining strategies on.

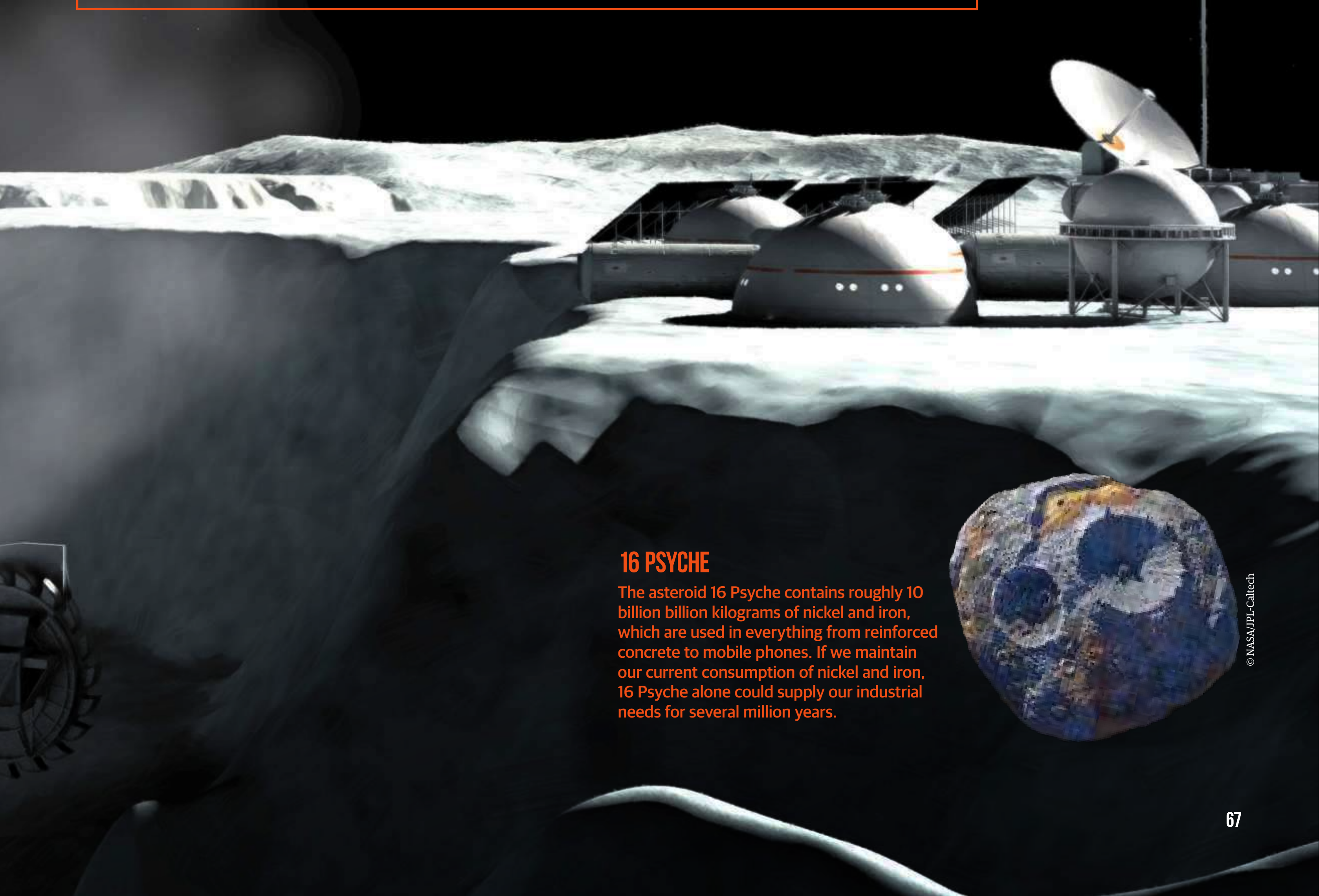


x2 Images © NASA

BIO

PAUL M. SUTTER

Sutter is a research professor in astrophysics at the Institute for Advanced Computational Science at Stony Brook University and a guest researcher at the Flatiron Institute in New York City. He is also the author of two books: *Your Place in the Universe* and *How to Die in Space.*



16 PSYCHE

The asteroid 16 Psyche contains roughly 10 billion billion kilograms of nickel and iron, which are used in everything from reinforced concrete to mobile phones. If we maintain our current consumption of nickel and iron, 16 Psyche alone could supply our industrial needs for several million years.

© NASA/JPL-Caltech

PLANET PROFILE JUPITER

The largest planet has a lot to tell us

Reported by Ian Evenden

Fifth in the eight-planet line-up of our Solar System, Jupiter also happens to be the largest, and by quite some distance. The mass of this gigantic ball of gas is two-and-a-half times that of all the other planets put together, and you could fit 11.2 Earths within its radius. While there's likely a rocky core somewhere under the enormous gaseous atmosphere, scientists can't be sure whether it's solid or not, but gravitational measurements suggest it could make up as much as 15 per cent of Jupiter's mass.

What is known is that Jupiter is contracting, and this generates more heat than the planet receives from the Sun, warming the huge number of moons that orbit around it. It also has a faint ring system, too thin to be seen from Earth with any but the largest telescopes and first spotted by the Voyager 1 probe in 1979.

Jupiter plays a major role in many theories of the formation of our Solar System. In one, known as the grand tack hypothesis, Jupiter formed at 3.5 AU – 1 AU is the Earth-Sun distance – before plunging inward towards the Sun until it reached 1.5 AU, then reversing course and moving out again, stopping at its current distance of 5.2 AU. It crossed the asteroid belt twice, scattering rocks in all directions and contributing to the low mass of the belt today. It may also have caused rocky planets orbiting closer to the Sun to crash into the star's surface. This answers questions such as why Mars is so small – Jupiter's presence limited the material available for its formation – and why there are no large planets orbiting close to the Sun, as we see in other solar systems.

Jupiter has also had a long-lasting effect on the rest of the Solar System. It has a fleet of asteroids and comets that follow it through its orbit – over 2,000 have been discovered – and its great mass means that the centre of gravity for it and the Sun lies above the Sun's surface, meaning they act almost like a binary system. The giant planet's gravity well also means it can intercept comets and asteroids heading into the inner Solar System, and may partially shield the inner planets from bombardment. Another theory, however, is that it actively draws small bodies in from the Kuiper Belt. Whichever is true, Jupiter experiences 200 times more impacts than Earth.

Visible with the naked eye from Earth, Jupiter represented the god Marduk to the Babylonians, and it was Phaethon to the ancient Greeks. The Romans assigned it to their king of the gods, whose name it bears today, whereas to Hindu astronomers it was Brihaspati, or Guru, which means 'heavy one'. Across Asia it was known as the Wood Star, a name taken from the Chinese theory of the five elements.

Galileo discovered Jupiter's four largest moons, known as the Galilean moons, in 1610, the first time moons had been observed around another planet. Humanity has since explored the planet with observatories and space probes, beginning in 1973 with a flyby by Pioneer 10. Many missions to the outer Solar System have used Jupiter's gravity as a slingshot to correct their course or gain speed, but the first craft to orbit the planet was the aptly named Galileo in 1995.

© NASA

Left: The hazy northern hemisphere of Jupiter processed by citizen scientist Gerald Eichstädt from Juno camera data in 2020

Above: A cyclonic storm in Jupiter's northern hemisphere, captured by Juno in 2019

Below: Pioneer 10 was the first human-made probe to cross the asteroid belt and fly past Jupiter

ATMOSPHERIC COMPOSITION

UPPER ATMOSPHERE

90%
HYDROGEN

10%
HELIUM

INTERIOR

71%
HYDROGEN

24%
HELIUM

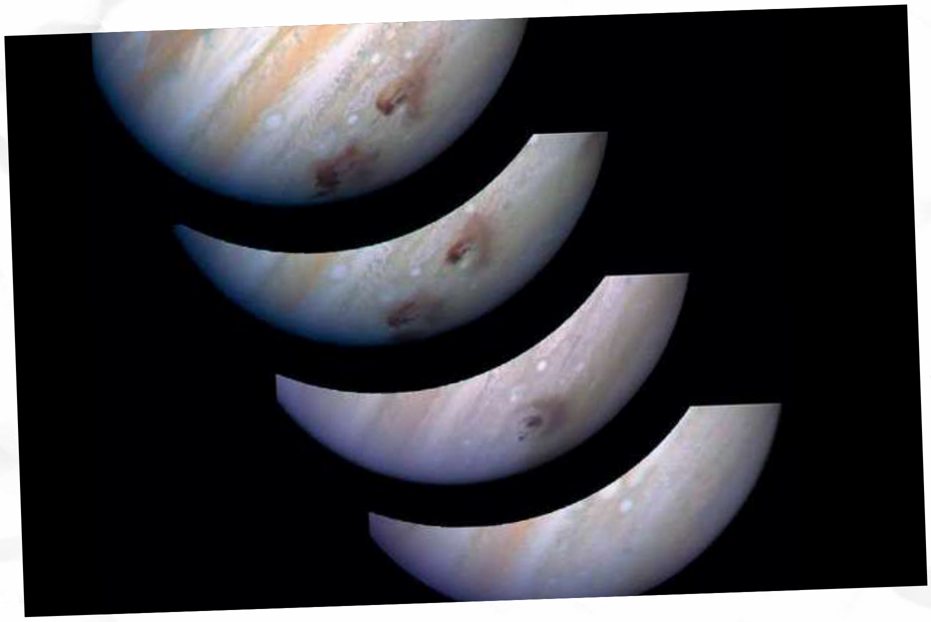
5%
OTHER ELEMENTS

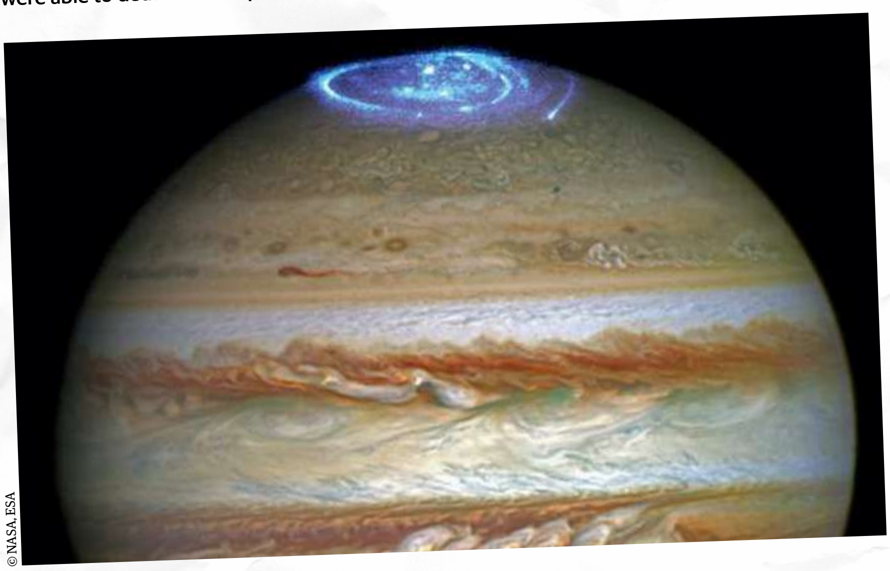
NEWS FROM JUPITER

WIND SPEEDS MEASURED

For the first time, scientists have been able to directly measure the winds in the middle of Jupiter's atmosphere. Using the Atacama Large Millimeter/submillimeter Array (ALMA), a team of astronomers was able to track the movement of molecules of hydrogen cyanide in the planet's famously turbulent atmosphere, measuring narrow bands of wind at up to 1,448 kilometres (900 miles) per hour. The hydrogen cyanide is not native to Jupiter, but was added to the storms when comet Shoemaker-Levy 9 collided with the giant planet in 1994. Since then it has been circling the atmosphere.

"The most spectacular result is the presence of strong jets, with speeds of up to 400 metres [1,312 feet] per second, which are located under the aurorae near the poles," said Thibault Cavalié of the Laboratoire d'Astrophysique de Bordeaux in France, who led the team behind the discovery. Using 42 of ALMA's 66 high-precision antennae, the team measured the Doppler shift, tiny changes in the radiation emitted by the molecules, from which they were able to deduce wind speed.





AURORAL ACTIVITY

Jupiter's version of the northern lights has puzzled scientists, because it doesn't behave like the aurorae on Earth. Here the lights appear in a ring between 60 and 70 degrees north or south of the equator. Within that ring, an area known as the 'polar cap', the lights don't appear. On Jupiter, however, there is no 'polar cap' – the aurora continues its display all the way to the pole.

This turns out to be due to a strange quirk of Jupiter's magnetic field. On Earth, the aurorae appear on closed field lines, which extend outwards from the planet before bending back again. Inside the 'polar cap' the field lines are open – they extend out into space – and there are no aurorae. Jupiter, meanwhile, has a mixture of open and closed field lines as you approach its poles, meaning the aurorae are still able to appear.

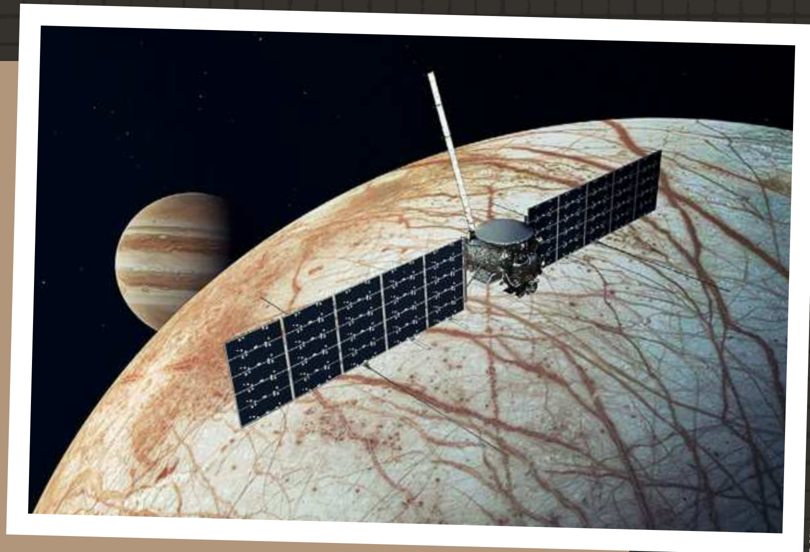
"We as a community tend to polarise, and couldn't imagine a solution where it was a little of both," said Peter Delamere, professor of space physics at the University of Alaska Fairbanks' Geophysical Institute.

ANOTHER JUPITER

Little is known about how planets as large as Jupiter form, but a planet circling another star, and under the watchful eye of the Hubble Space Telescope, could give us a lot of information. Known as PDS 70b, the planet orbits a very young orange dwarf 370 light years away in the southern constellation of Centaurus, which has two actively forming planets within its protoplanetary disc. PDS 70b, which orbits the star at the same distance as Uranus orbits our Sun, is already around five times the mass of Jupiter, and possibly twice as large, and at a mere 5 million years old should continue to form for a little while yet, though the rate at which it is accreting more material has dwindled.

"This system is so exciting because we can witness the formation of a planet," said Yifan Zhou of the University of Texas at Austin. "This is the youngest bona fide planet Hubble has ever directly imaged; observations allowed us to estimate how fast the planet is gaining mass." Magnetic field lines turn out to play a role in the formation of such a planet, extending from the disc of dust and gas that surrounds the young star and funnelling material onto the planet's surface.

FUTURE PLANS FOR JUPITER



© NASA/JPL-Caltech

Above: Europa is the target of many space agencies, which are keen to explore its life-hosting potential

While Jupiter has been heavily photographed by missions such as Juno, which arrived at the planet in 2016, much scientific interest has now transferred to the planet's moons, which are thought to harbour subsurface liquid oceans and possibly even life. Europa, Ganymede and Callisto, three of the Galilean moons, would be the targets, but multiple missions have been cancelled due to lack of budget.

In 2024 NASA's Europa Clipper should launch, following up on studies from the Galileo probe and performing multiple flybys of Europa without orbiting it, using the gravity of nearby moons to change its course. The European Space Agency will send its Jupiter Icy Moons Explorer in 2022 to study Ganymede, Callisto and Europa, evaluating their potential to support life. Other countries also have their eyes on the giant planet, with China's Gan De proposed for launch in 2029 and an unnamed Russian proposal to use a nuclear-powered tug to travel to the planet sometime after 2030.

Further into the future, Europa is seen as a potential site for human colonisation of the Solar System, as it is geologically stable and levels of radiation are low there. Low is a relative term, however, as unshielded colonists would receive 5.4 sieverts of radiation per day from Jupiter, compared to 0.0024 sieverts per year on Earth. This is still enough to cause radiation poisoning.

JUPITER BY NUMBERS

24,000°C
The estimated temperature at Jupiter's core

11.8 YEARS
Jupiter's orbit around the Sun

5,000KM
The thickness of Jupiter's atmosphere, the deepest in the Solar System

79
known moons circulate around Jupiter

1665
Jupiter's Great Red Spot is a storm known to have existed since at least 1831, and maybe even since 1665

14x
Jupiter's magnetic field is 14 times stronger than Earth's, and the strongest in the Solar System except for sunspots

4TH
Fourth-brightest object in the sky as seen from Earth

EVOLUTION OF THE JOVIAN GIANT

Date: 4.6 billion years ago
Activity: The Solar System began to form from a cloud of gas and dust around a new star

Date: 4.596 billion years ago
Activity: Jupiter and Saturn began to take shape

Date: 2400 BCE
Activity: Babylonians tracked a full cycle of Jupiter's movement across the skies

Date: 270 BCE
Activity: Jupiter was part of Aristarchus of Samos' heliocentric model of the Solar System

Date: 1610
Activity: Galileo discovered the Galilean moons: Ganymede, Callisto, Io and Europa

Date: 1892
Activity: Edward Emerson Barnard discovered a fifth moon of Jupiter, Amalthea

Date: December 1974
Activity: Pioneer 11 passed within 42,500 kilometres (26,400 miles) of Jupiter's cloud tops

Date: January 1979
Activity: Voyager 1 reached the gas giant planet

Date: December 1995
Activity: The Galileo probe entered Jupiter orbit

Date: July 2016
Activity: The Juno probe entered a polar orbit around the planet

"MUCH SCIENTIFIC INTEREST HAS NOW TRANSFERRED TO THE PLANET'S MOONS"

MOON PROFILE EUROPA

One of the Solar System's famous ocean worlds is an exciting prospect for further exploration

Europa is one of the four Galilean moons that orbit the Solar System's largest planet, Jupiter. Although Europa is the smallest of its satellite siblings – Io, Callisto and Ganymede, carrying on in that order from smallest to largest – it is certainly the one with the most potential for exciting scientific discovery. Underneath its icy, scarred surface could lie a salty ocean, just like the oceans that make up 71 per cent of the Earth's surface.

The Galilean moons were discovered in 1610 by Italian astronomer Galileo Galilei, and through the ages astronomers have been fixating their telescopes on the speck of light that orbits Jupiter once every three-and-a-half days. Europa is also tidally locked to Jupiter, meaning that the same face of the moon is pointing at the Jovian giant at all times, much like the Moon and Earth. Another similarity is the two moons' sizes: Europa has an equatorial diameter of 3,100 kilometres (1,940 miles), which is 90 per cent of the Moon's diameter. If you were to replace the Moon with Europa in our sky, to the naked eye they would both seem about the same size. However, Europa would be much brighter on account of its surface ice reflecting 5.5-times more sunlight than the Moon.

"UNDERNEATH ITS ICY, SCARRED SURFACE COULD LIE A SALTY OCEAN"

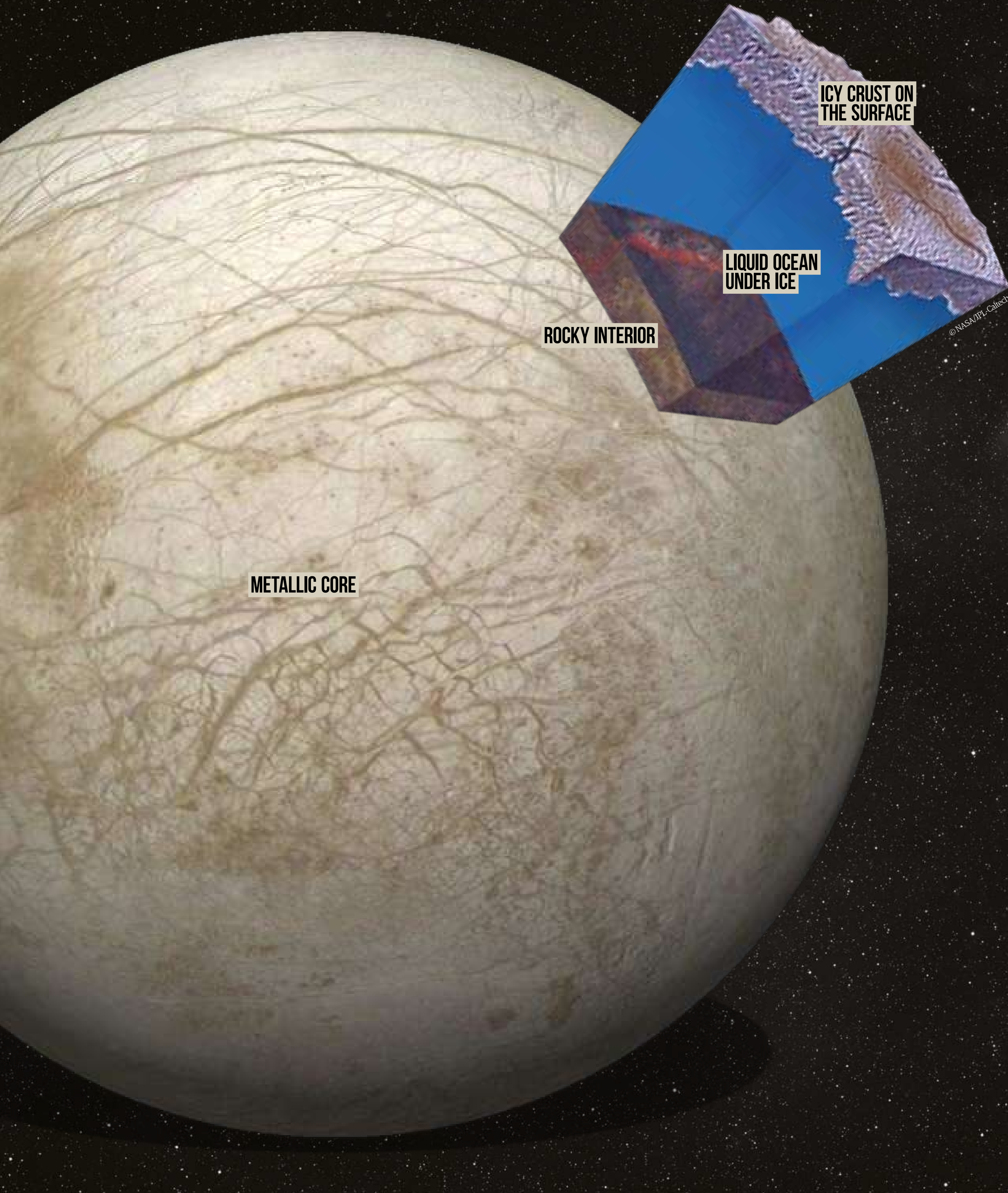
© NASA/JPL-Caltech

The process behind the creation of Jupiter's largest moons is still hotly debated, but astronomers largely agree that they formed from leftover debris from the formation of Jupiter roughly 4.5 billion years ago. Fast-forward to today and Europa is a water-ice ball with fractures criss-crossing all over the surface. The number of craters currently found all over its cracked terrain indicate that the moon is no older than 90 million years old, suggesting there is likely to be some form of surface replenishment that also brings salts and sulphur compounds to the outer layer. Surrounding the icy world is a thin atmosphere, composed of molecular oxygen.

The core is most likely made of iron, surrounded by a tough, rocky mantle. In between that and the icy crust is a suspected body of liquid. Some may wonder how such a small world, so far away from the heat of the Sun, can maintain an ocean of salty water similar to Earth's. The answer is that it's likely due to the grand gravitational effects of Jupiter, pulling and pushing the insides of Europa, causing it to heat up and, in turn, transforming ice into water. This process is known as 'tidal heating', and it can be observed happening with grander effect on fellow moon Io – its interior is heated up to such an extent that volcanoes have popped up.

This tidal heating is what maintains the ocean and provides the energy to replenish the surface via the outburst of plumes or a form of icy plate tectonics. Ever since astronomers became aware of the vitalising interior of Europa, they have pieced together that it has the fundamental building blocks for life to exist: liquid water, chemical compounds for consumption and an energy source. For this reason especially, planetary scientists are excited to return to the Galilean moon. There is a high chance that life could exist in this part of the Solar System, even if it's just in the form of simple microbes.

Left: This shows almost-pure water ice, shown in white, broken up by contaminated water ice, shown in red


ICY CRUST ON THE SURFACE
LIQUID OCEAN UNDER ICE
ROCKY INTERIOR
METALLIC CORE
© NASA/JPL-Caltech

WHAT'S BEEN HAPPENING AT EUROPA?

TABLE SALT FOUND SPRINKLED ON THE SURFACE

Europa has had visitors in the past, notably NASA's Voyager and Galileo spacecraft. On their flybys of the moon, analyses showed that the icy crust consisted of water ice and a substance originally thought to be magnesium sulphate. After recently revisiting the surface using the W. M. Keck Observatory based in Hawaii and the Hubble Space Telescope, astronomers now know that it wasn't magnesium sulphate and was actually sodium chloride – more commonly known as table salt.

As Voyager and Galileo had only an infrared spectrometer to work with, they couldn't see what was hiding in the visible light spectrum. Keck and Hubble were able to unveil the hidden secret. "We thought that we might be seeing sodium chlorides, but they are essentially featureless in an infrared spectrum," says Mike Brown, the Richard and Barbara Rosenberg professor of planetary astronomy at Caltech in Pasadena, California.

It was some laboratory tests by Kevin Hand at NASA's Jet Propulsion Laboratory, also in Pasadena, that revealed that irradiating ocean salts under Europa-like conditions exhibit distinct features and a yellowish colour – table salt exhibits this colour on the surface of Europa, confirming its presence.

SETBACKS FOR EUROPA'S NEXT EXPLORER

NASA has its sights set on sending two very ambitious missions to Europa, one of which is due to launch in 2023. Unfortunately the Europa Clipper mission, an orbiter that will spend about three years at the moon, and the proceeding Europa Lander mission seem to have come under scrutiny after a nine-month investigation concluded that there are serious issues that need to be addressed in order to satisfy both NASA and the United States Congress.

"Our audit found that despite robust early stage funding, NASA's aggressive development schedule, a stringent conflict-of-interest process during instrument selection, an insufficient evaluation of cost and schedule estimates and technical workforce shortages have increased instrument integration challenges and development risks for the Clipper mission," John Schultz, a management analyst at the Office of Inspector General, said in a statement.

After finding these conflicts of interest and issues in the budget, the investigation team have concluded that ten changes should be made in order to get the project back on track, including altering the overall staffing regime, rescheduling milestones and making sure that any estimates be made in accordance with other projects.

STRUGGLING TO FIND THE PLUMES

Europa is a moon that shares many similarities with Saturn's moon Enceladus – both are icy worlds that exhibit signs of a subsurface ocean that could harbour potential life. One major difference though is that Enceladus has been studied much more thoroughly, courtesy of NASA's Cassini mission. In this close-up analysis Cassini detected plumes of material emerging from the surface of Enceladus, along with a distinct temperature spike in the data to match. However, this doesn't appear to be the same for Europa.

"We searched through the available Galileo thermal data at the locations proposed as the sites of potential plumes. Reanalysis of temperature data from the Galileo mission does not show anything special in the locations where plumes have possibly been observed. There are no hotspot signatures at either of the sites," says Julie Rathbun, a senior scientist at the Planetary Science Institute. "This is surprising because the Enceladus plumes have a clear thermal signature at their site of origin, so this suggests that either the Europa plumes are very different, or the plumes are only occasional, that they don't exist or that their thermal signature is too small to have been detected by current data."

THE PAST AND FUTURE OF EXPLORATION

Being part of the Jovian system has its benefits in terms of exploration. Although Europa hasn't had the same close inspection as Enceladus, many spacecraft have made a flying visit of the moon as they use Jupiter's enormous mass to provide a 'gravity assist' – when a spacecraft uses a planet's mass to slingshot it to a faster speed.

The first of these visits began with NASA's Pioneer 10 and 11 in 1973 and 1974 respectively. Afterwards came the two Voyager spacecraft in 1979, sending back pictures of Europa's icy surface in stunning resolution.

This began speculation that the moon had a subsurface ocean, gathering traction when NASA's Galileo spacecraft spent eight years at the Jovian system, starting in 1995. This long-duration study revealed a host of exciting new discoveries about Europa and its fellow moons. The last spacecraft to visit Europa was NASA's New Horizons in 2007 when it tested its equipment at the Jovian system on the way to Pluto. The future is very exciting for the Galilean moons. Two major space exploration organisations, the European Space Agency (ESA) and NASA, are looking to visit. Due to launch in June 2022 is the ESA's JUpiter ICy moons Explorer (JUICE), which will head to the system in order to study Ganymede, Callisto and Europa. The following year – assuming there are no delays from the aforementioned investigation – NASA will launch its Europa Clipper, solely focused on studying Europa.

After much discussion the Europa Clipper team decided that, due to Jupiter's radiation, it would be best to put the orbiter in an elliptical orbit that makes 45 close flybys over the course of roughly three years. In a separate mission there will be a Europa Lander that will complement the Europa Clipper.

Europa is one of the most reflective objects in the Solar System because of its icy surface

NASA'S TIMELINE OF EUROPA VISITORS

- **Date:** 3 December 1973
  Spacecraft: Pioneer 10
- **Date:** 3 December 1974
  Spacecraft: Pioneer 11
- **Date:** 5 March 1979
  Spacecraft: Voyager 1
- **Date:** 9 July 1979
  Spacecraft: Voyager 2
- **Date:** 8 December 1995 to 21 September 2003
  Spacecraft: Galileo
- **Date:** 28 February 2007
  Spacecraft: New Horizons

EUROPA FACTS

671,100 KM

Europa orbits Jupiter at a distance of 671,100 kilometres (417,000 miles), almost double that of the Earth-Moon distance.

Europa is the smoothest object in the Solar System, lacking more craters and mountains than any other object.

Hydrothermal vents could exist on the seabed of Europa, similar to what is seen on the floor of Earth's oceans – a region where extremophiles thrive.

Europa is stuck in an orbital resonance with two fellow Galilean moons; for every orbit Ganymede completes, Europa does two and Io completes four.

All of Jupiter's moons are named after the lovers of Zeus from Greek mythology; Europa was the queen of Crete.

Europa's surface temperature at the equator never reaches higher than -160 degrees Celsius (-260 degrees Fahrenheit).

-160°

The cracks on the surface of the moon are thought to be from the constant movement of the subsurface sea when it gets too close to Jupiter.

PLANET PROFILE
SATURN

Saturn is famous for its rings, but there is more to it than meets the eye

The Ringed Planet is not only a fan favourite among astronomers because of its consistent visibility in the night sky, but also because it offers an enticing uniqueness. Along with Jupiter, Uranus and Neptune, Saturn is one of the gas giants – also known as Jovian planets – that sit in the outer regions of the Solar System. What is most intriguing about the two largest planets in our Solar System, Jupiter and Saturn, is that they are the bridge to understanding stars like our Sun. Although they are classified as planets, they have a more similar composition to the Sun than they do to Earth.

Saturn is one of the brightest objects in the night sky, with an apparent magnitude that swings from -0.55 to +1.17. Magnitude varies with the distances between Saturn, Earth and the Sun. The ringed gas giant is nine-times further away from the Sun than Earth is, as well as over nine times the Earth's diameter. As the second-largest planet Saturn also has an enormous volume capacity, which is capable of fitting 764 Earths inside it.

As it is an extremely bright celestial object, Saturn has been observed for centuries, and as such its discovery date can't be pinned down. However, the Italian astronomer Galileo Galilei observed Saturn through his telescope in 1610, at first believing that Saturn's rings were actually moons. Over years of observation the moons would change shape and sometimes disappear, which was due to the planet's inclination with respect to Earth. Galileo's error wasn't realised until 45 years later when Dutch astronomer Christiaan Huygens used a telescope with a higher resolution to resolve the rings.

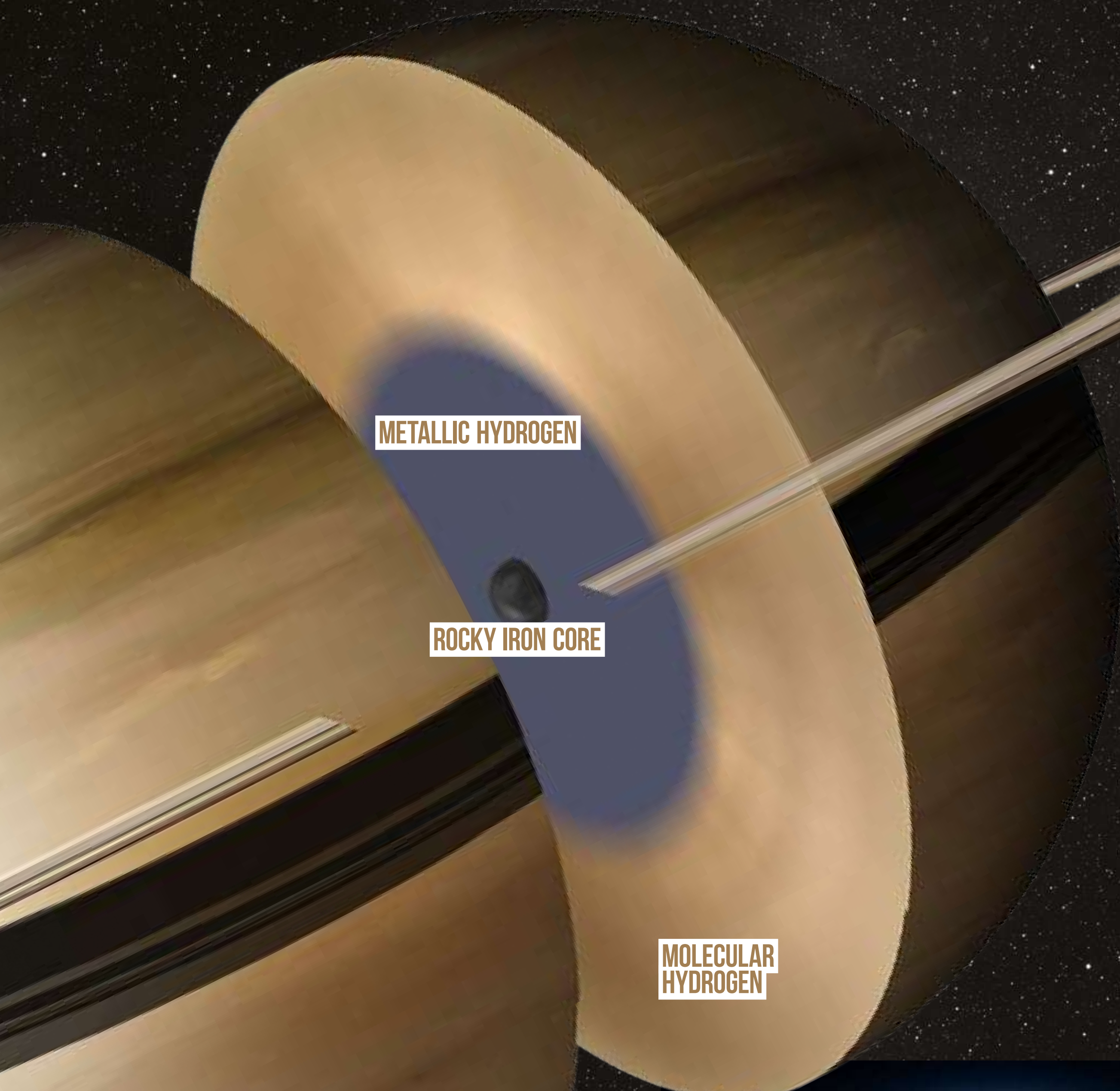
In modern times space probes have been able to get a much closer look at the planet and its ring structure, the most prominent example being NASA's Cassini spacecraft. Cassini's flybys showed that Saturn's rings are made up of mostly water-ice particles and some rocky meteoroids, sized from tiny grains of sand to as large as mountains and extending up to 282,000 kilometres (175,000 miles) from the planet.

There is much more to Saturn than just its rings though. It has 53 confirmed moons, with a further 29 provisional moons that are just awaiting confirmation. The most intriguing moons are Titan and Enceladus, which exhibit exciting astrobiological prospects. Titan shows Earth-like weather cycles and lakes, but with hydrocarbons, and Enceladus has a subsurface ocean of liquid salty water. Saturn in itself is an enormous and fascinating structure that has become more and more understood since the days of Galileo and Huygens.

As mentioned previously, Saturn is more similar to the Sun than it is the Earth. The planet's composition is 94 per cent hydrogen and six per cent helium, with trace amounts of methane and ammonia. While astronomers can't physically dig down into Saturn and see its internal structure, they can build computer models showing how the planet formed 4.6 billion years ago. These models show that as temperatures and pressures rise as you get closer to the core, gaseous hydrogen is squashed into liquid metallic hydrogen. At the core of Saturn is a rocky ball of denser elements, including iron and nickel.

"SPACE PROBES HAVE BEEN ABLE TO GET A MUCH CLOSER LOOK AT THE PLANET AND ITS RING STRUCTURE"

The Cassini space probe spent 13 glorious years scrutinising the Saturnian system



SATURN COMPOSITION

94%

HYDROGEN

6%

HELIUM

+

TRACES OF AMMONIA AND METHANE

This is the famous image titled 'The Day the Earth Smiled'

THE LATEST NEWS FROM SATURN

TITAN SURVIVED SATURN'S ANCIENT FEEDING FRENZY

It's likely that when Saturn was in its younger years, it was accreting whatever mass it could to become the enormous size it is now. In this primordial feeding frenzy, natural satellites orbiting close to the surface were likely engulfed on account of Saturn's gravity. Yet Titan, the second-largest natural satellite in the Solar System behind Jupiter's Ganymede, has remained in orbit.

Yuri Fujii, a designated assistant professor at Nagoya University, and Masahiro Ogihara, a project assistant professor at the National Astronomical Observatory of Japan (NAOJ) have recently proposed that Titan was spared from this frenzy due to a 'safety zone' created by the warmer and closer gas. In this scenario, the inner gas pushes a large moon away from Saturn and stops it from being consumed.

"We demonstrated for the first time that a system with only one large moon around a giant planet can form," said Fujii. "This is an important milestone to understand the origin of Titan." Not only does it help explain the origin of Titan, but it also helps explain why Saturn only has the one relatively huge moon. The next biggest Saturnian moon is Rhea, which is less than a third the size of Titan.

© Nagoya University

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WHAT HAPPENS TO SATURN WHEN THE SUN TURNS INTO A WHITE DWARF?

In approximately 5 billion years our Sun will have swallowed the rocky terrestrial planets, including Earth, as it entered the red supergiant phase of its lifetime. After a further 3 billion years the supergiant star will have shed its outer layers and left behind a white dwarf star. This is the dense, scorching-hot remnant of the star we know now.

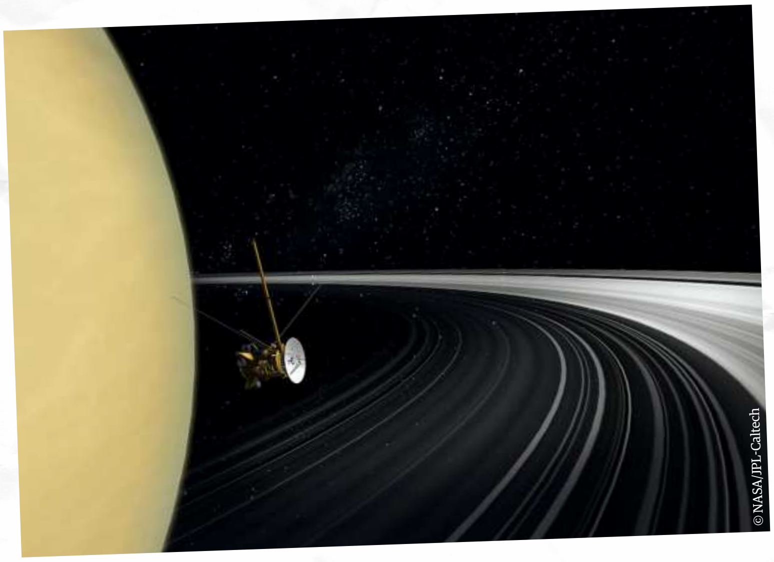
Recent research conducted by Matthias Schreiber, an astrophysicist at the Universidad de Valparaíso in Chile, suggests that once a Sun-like star has transformed into a white dwarf, it would be able to accrete the evaporated layers of its surrounding gas giant planets. This research has very intriguing implications for the future evolution of the Solar System, and in particular the ability to spot signs of Saturn in a white dwarf star.

As Schreiber said, "The white dwarf will accrete a fraction of the evaporated material, and this will result in detectable signatures, so future generations of alien astronomers, if they exist, can potentially investigate the chemical composition of Jupiter, Saturn, Neptune and Uranus."

LORD OF THE RINGS: THE TWO EXPLANATIONS

The origin of Saturn's rings has been subject to constant debate since their discovery. While some believe they formed during the formation of the planet 4.6 billion years ago, others think they could have arisen within the last couple of hundred million years. Recent research by Aurélien Crida of the Observatoire de la Côte d'Azur argues that they are most likely ancient, based on data taken during the Cassini mission's 'Grand Finale', which consisted of a series of dives through Saturn's rings before vaporising in the atmosphere. During this time Cassini measured the mass of the ring system as about 15.4 million billion tonnes. That's equivalent to about 40 per cent the mass of Saturn's moon Mimas, which is 400 kilometres (250 miles) wide.

Some argue that because the rings are more than 95 per cent water ice, they should be more contaminated if they are ancient. However, Crida has provided evidence that suggests the mass of Saturn's rings is consistent with 4.6 billion years of very dynamic evolution. "I think that, objectively, [this theory] forms a much more consistent picture, with a convincing model of their formation at the same time as Saturn, plus formation and outward migration of the satellites in agreement with the observations", said Crida.



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THE HISTORY OF SATURNIAN EXPLORATION

Saturn has been extensively studied across centuries. When Galileo used his telescope in the early 17th century, the rings of Saturn became apparent. Fast forward to 2020 and there is a host of commercially available telescopes to see the planet in amazing clarity. There is also a team of ground- and space-based observatories that frequently capture observations of the planet to provide regular updates.

In regards to space probe missions to Saturn, it has had a handful of human-made mechanical visitors over the last few decades. The first interplanetary investigator was NASA's Pioneer 11 spacecraft; it became the first probe to encounter Saturn on 1 September 1979. After that were NASA's two Voyager probes, which returned historic images of the outer Solar System, discovering moons and revealing surface features that had never been seen before. Voyager 1 flew past Saturn on 12 November 1980 and Voyager 2 followed suit on 26 August 1981.

The most fruitful mission to Saturn arrived there on 1 July 2004. The Cassini space probe – created in a collaboration between NASA, the European Space Agency (ESA) and the Agenzia Spaziale Italiana (ASI) – stayed in orbit around the Ringed Planet for 13 years, and the ESA-built Huygens lander arrived on the surface of Titan on 14 January 2005. For over a decade this probe took magnificent images, collected pivotal data and even took the first dive through the planet's rings. During this 'Grand Finale', as it was known, the space probe was able to collect unprecedented data on the Cassini Division, which is the wide gap between rings A and B.

This mission is still fresh in the memory of astronomers, as they are still examining heaps of data collected during Cassini's stay at Saturn. This means that we're unlikely to see a Saturn-specific mission in the foreseeable future. Do not give up hope though, as there are certainly talks of returning to its moons. For example, NASA's Dragonfly mission is hoping to launch a drone to the surface of Titan by 2026.

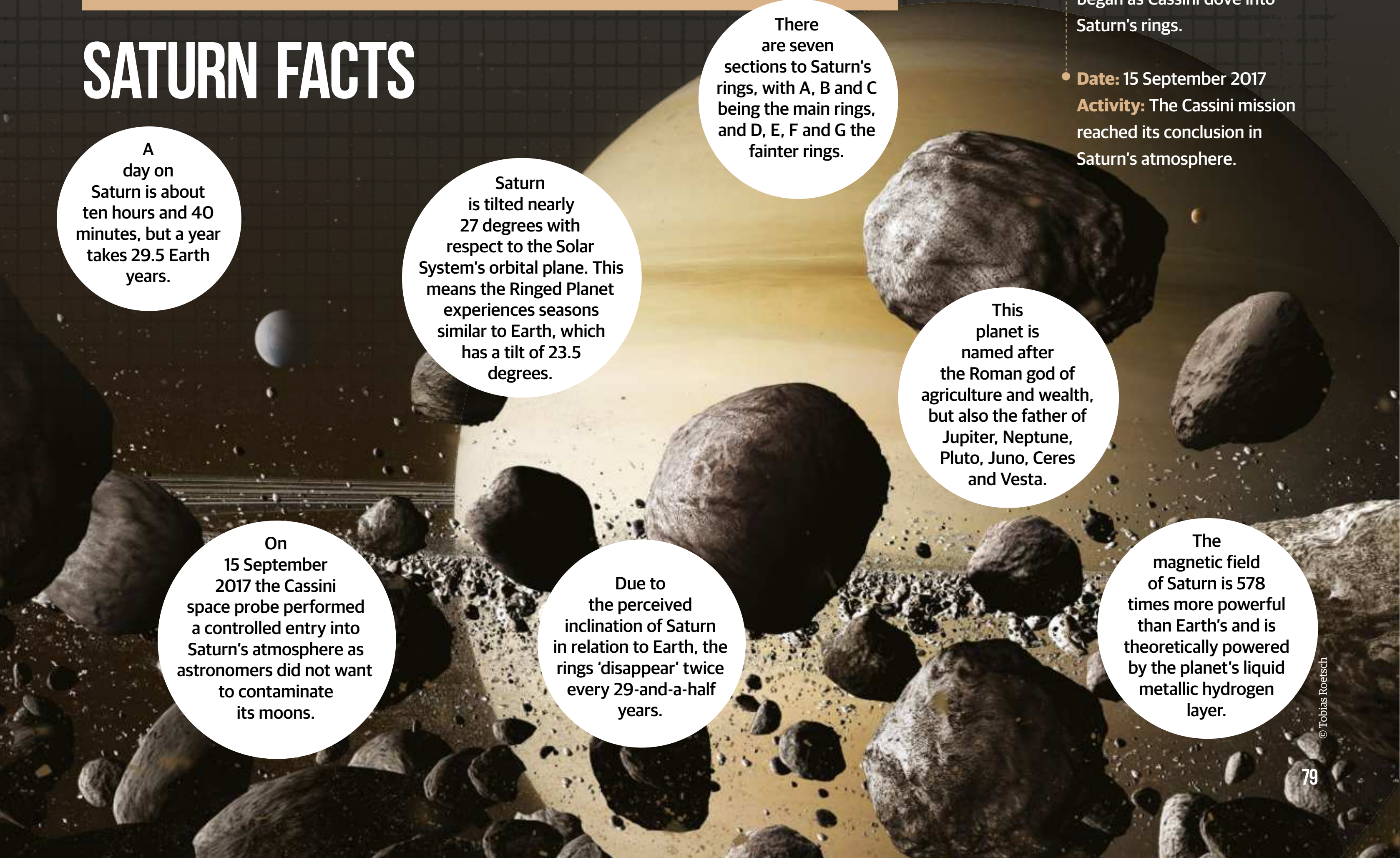
Below: The Dragonfly mission will examine Saturn's largest moon, Titan

© Adrian Mann

A TIMELINE OF CASSINI-HUYGENS' VOYAGE TO SATURN

- **Date:** 15 October 1997
  Activity: Cassini-Huygens was launched from Cape Canaveral.
- **Date:** 30 December 2000
  Activity: The spacecraft passed Jupiter to conduct a gravity-assist manoeuvre.
- **Date:** 1 July 2004
  Activity: The Cassini-Huygens space probe arrived at Saturn.
- **Date:** 14 January 2005
  Activity: The Huygens probe separated from Cassini and landed on the surface of the moon Titan.
- **Date:** 19 July 2013
  Activity: Cassini took the historic picture of Earth from Saturn titled 'The Day the Earth Smiled'.
- **Date:** 29 November 2016
  Activity: The Grand Finale began as Cassini dove into Saturn's rings.
- **Date:** 15 September 2017
  Activity: The Cassini mission reached its conclusion in Saturn's atmosphere.

SATURN FACTS



A day on Saturn is about ten hours and 40 minutes, but a year takes 29.5 Earth years.

Saturn is tilted nearly 27 degrees with respect to the Solar System's orbital plane. This means the Ringed Planet experiences seasons similar to Earth, which has a tilt of 23.5 degrees.

There are seven sections to Saturn's rings, with A, B and C being the main rings, and D, E, F and G the fainter rings.

This planet is named after the Roman god of agriculture and wealth, but also the father of Jupiter, Neptune, Pluto, Juno, Ceres and Vesta.

On 15 September 2017 the Cassini space probe performed a controlled entry into Saturn's atmosphere as astronomers did not want to contaminate its moons.

Due to the perceived inclination of Saturn in relation to Earth, the rings 'disappear' twice every 29-and-a-half years.

The magnetic field of Saturn is 578 times more powerful than Earth's and is theoretically powered by the planet's liquid metallic hydrogen layer.

© Tobias Roetsch

MOON PROFILE
MIMAS

This small, oddly shaped and icy moon continues to baffle scientists

You could be mistaken in thinking this strange satellite is something pulled straight out of the *Star Wars* universe. Commonly referred to as the 'Death Star' moon, Mimas has only been visited a few times, and could be harbouring secrets below its surface.

Discovered on 17 September 1789 by William Herschel, and later named by his son John Herschel, Mimas is Saturn's smallest and innermost major moon. Orbiting just 185,539 kilometres (115,300 miles) above the gas giant, the icy moon zips along at high speeds, completing an orbit in just 22 hours and 36 minutes. Akin to our own Moon, Mimas is tidally locked with its host, meaning it keeps the same face towards Saturn as it orbits the planet.

The dinky moon has a mean radius of less than 198 kilometres (123 miles), and as such it is not quite large enough to hold a classic round moon shape. Instead Mimas displays rather odd dimensions of 207 by 197 by 191 kilometres (129 by 122 by 119 miles). The surface of the icy moon is peppered with craters of varying size, with some measuring over 40 kilometres (25 miles) in diameter. The most conspicuous is Herschel, named after Mimas' discoverer, a substantial feature that dominates the landscape and stretches for over 130 kilometres (80 miles).

Some of the moon's formation history can be inferred by the heavily cratered landscape, particularly at the south pole region. Here the craters are generally half the size of anywhere else on Mimas, which would suggest the moon experienced some melting or other resurfacing processes that occurred in this region later than the rest of the celestial body. However, due to limited data and observations of the icy satellite, scientists cannot yet determine the cause of the possible resurfacing.

Mimas continues to perplex scientists with its rather strange composition, as the frozen moon is primarily made from water ice. However, at first glance this composition in itself is not strange, as Mimas is not the only icy moon in the Saturnian system. It is joined by Tethys, Rhea and Dione, as well as Saturn's sixth-largest moon Enceladus, which is thought to possess a liquid ocean below its icy crust.

However, unlike these other icy bodies, Mimas is much closer to Saturn and has a far more eccentric orbit. Compared to Enceladus, Mimas should experience more tidal heating due to its position and orbit. However, it's Enceladus that boasts geysers of water that suggest the presence of internal heat, while Mimas remains both frozen and heavily cratered, suggesting that the surface has persisted in this frozen state for a very long time. This paradox has led astronomers to develop the 'Mimas test', by which any theory used to explain the partially thawed water of Enceladus must also explain the entirely frozen water of Mimas.

With its strange dimensions, peculiar composition and quirky appearance earning it a revered place in pop culture, this enigmatic little moon undoubtedly has many more secrets to spill.

Left: This image was taken by Cassini in 2008 shows Mimas against the ring of Saturn

COMPOSITION

100%

WATER ICE AND SMALL AMOUNTS OF SILICATE ROCK

"MIMAS CONTINUES TO PERPLEX SCIENTISTS WITH ITS RATHER STRANGE COMPOSITION"

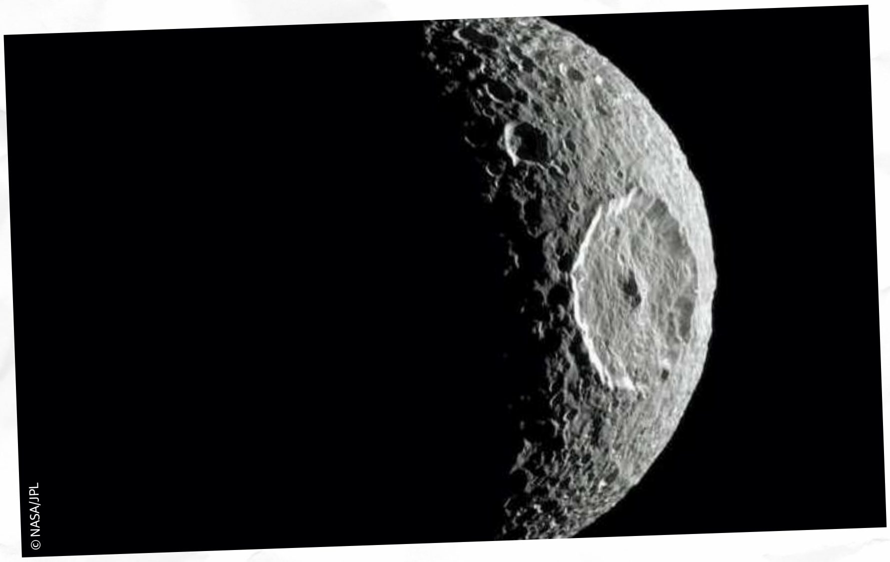
NEWS FROM MIMAS

MIMAS PLOUGHS THROUGH SATURN'S RINGS

Mimas may be the smallest of Saturn's major moons, but it sure is mighty. The tiny, icy body has cleared enough material to create a 4,800-kilometre (2,980-mile) wide gap between Saturn's two largest rings. This void is known as the Cassini Division after its discoverer Giovanni Cassini, who observed it in 1675, and is located between Saturn's A and B rings.

The formation of the Cassini Division had been poorly understood until scientists suggested that Mimas acted as a snowplough, clearing the ice particles that make up the rings from its path and paving the way for the substantial gap.

Mimas is thought to have migrated inwards towards Saturn by approximately 9,000 kilometres (5,600 miles) over a few million years – relatively recently in cosmic terms – leading to the widening of the original gap and the establishment of the Cassini Division. This rift will not last forever, as Mimas has begun to migrate outwards, and in about 40 million years the Cassini Division will have closed up again.



WHAT'S BEHIND MIMAS' WOBBLE?

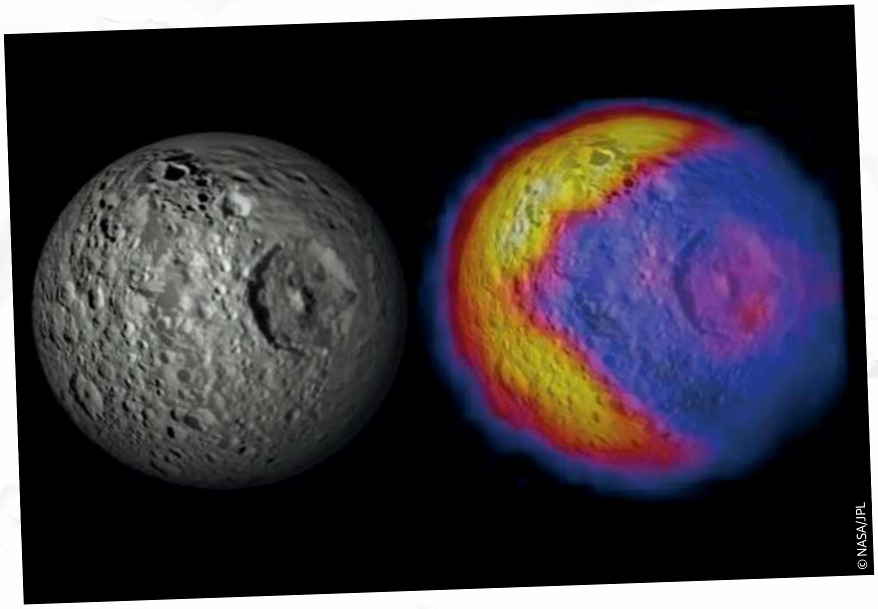
In 2014, scientists analysing data collected from Cassini noticed the moon librates (wobbles) around its polar axis. While this isn't unusual, with libration being observed in many moons, the surprise came when the libration was measured. Mimas' wobble is double than expected and is more pronounced in one spot, suggesting that Mimas' interior is not uniform. Scientists suggested the heavily cratered surface is masking one of two interesting possibilities. One is that the moon contains a rather odd, rugby ball-shaped core, and the other is that there are different materials or densities of material below the icy shell, such as a subsurface ocean.

Since the discovery, scientists have been unable to confirm or deny any of these possibilities, and many questions remain unanswered. If Mimas has an oval-shaped core, we'd expect the moon to take on a slightly different shape to the one we see. And if there's a subsurface ocean, how does Mimas source the heat energy to maintain such an ocean?

PECULIAR SURFACE TEMPERATURES GIVE RISE TO A 'PAC-MAN' MOON

During the Cassini flyby of Mimas on 13 February 2010, an unexpected pattern of daytime temperatures was observed on the little moon's surface. When the Composite Infrared Spectrometer (CIRS) data was analysed and then mapped onto a visible-light image of Mimas, a strange Pac-Man like scene was presented across the moon's surface.

This baffled scientists, who expected to see a uniform distribution of surface temperatures that were highest in the early afternoon, similar to what we see on Earth. Instead Mimas appears to be divided into a warm part (left) and a cold part (right), with a V-shaped boundary between them. Typical temperatures in the warmer region were around -181 degrees Celsius (-294 degrees Fahrenheit), while the colder region saw temperatures drop to -196 degrees Celsius (-320 degrees Fahrenheit). The stark difference between the regions could be due to thermal conductivity of the surface material. If the colder region is made up of surface materials with a higher thermal conductivity, then more of the Sun's heat will be soaked into the subsurface instead of warming the material itself.

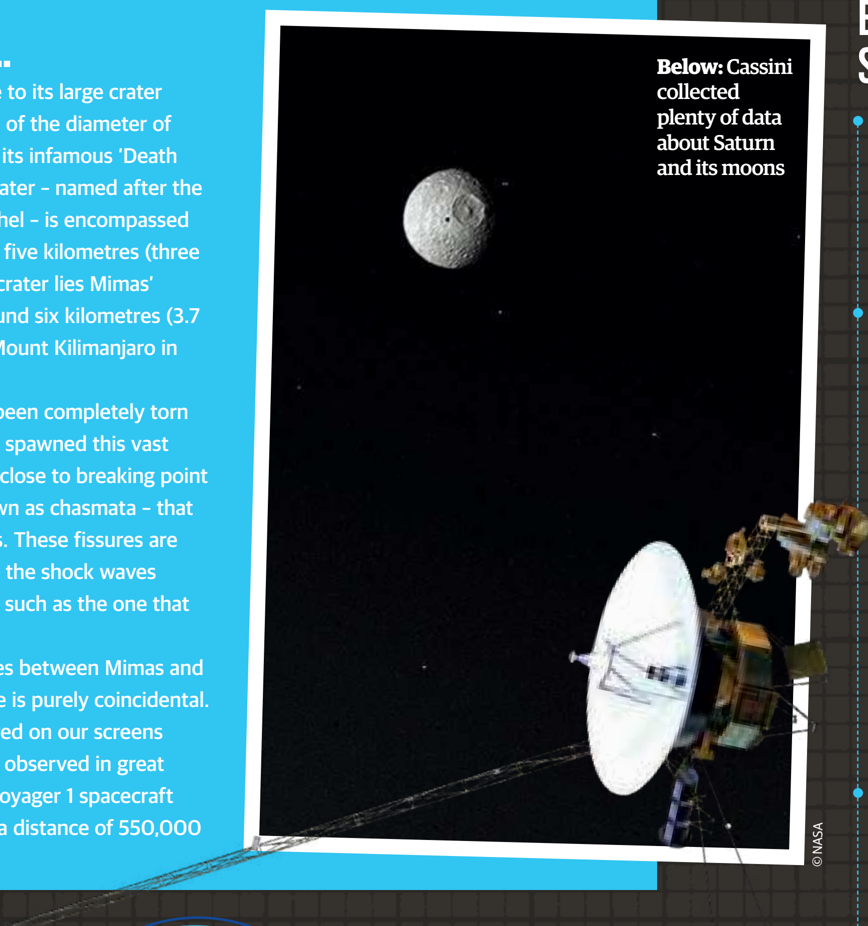


THAT'S NO MOON...

Mimas owes its pop culture fame to its large crater Herschel, which covers one-third of the diameter of the moon itself and gives Mimas its infamous 'Death Star' appearance. The massive crater – named after the moon's discoverer William Herschel – is encompassed by towering outer walls standing five kilometres (three miles) high. At the centre of the crater lies Mimas' mountain, an imposing peak around six kilometres (3.7 miles) high – slightly taller than Mount Kilimanjaro in Tanzania, Africa.

Mimas was lucky not to have been completely torn apart by the colossal impact that spawned this vast crater. Evidence that Mimas was close to breaking point comes from fractures – also known as chasmata – that lie on the opposite side of Mimas. These fissures are thought to have been created by the shock waves generated from a sizable impact, such as the one that created Herschel crater.

Despite the uncanny similarities between Mimas and the Death Star, their resemblance is purely coincidental. While the Death Star first appeared on our screens in the late 1970s, Mimas was not observed in great detail until 1980, when NASA's Voyager 1 spacecraft photographed the satellite from a distance of 550,000 kilometres (340,000 miles).



Below: Cassini collected plenty of data about Saturn and its moons

MIMAS BY NUMBERS

22.5 HOURS
The time it takes Mimas to complete one orbit of Saturn

185,539 KILOMETRES
The distance between Mimas and Saturn

198KM
Mean radius of the icy moon

32,038 MILES PER HOUR
Speed at which Mimas orbits Saturn

8.8
How many times smaller Mimas is compared to Earth's Moon

FOUR
The number of spacecraft that have visited Mimas: Pioneer 11, Voyager 1, Voyager 2 and Cassini-Huygens

1789
The year Mimas was discovered by William Herschel

493,647.75 SQUARE KILOMETRES
The surface area of Mimas, slightly less than the land area of Spain

EXPLORATION OF SATURN'S SYSTEM

Date: 31 August 1979
Activity: Pioneer 11 detected Saturn's bow shock – the first conclusive evidence that Saturn has a magnetic field.

Date: 1 September 1979
Activity: Pioneer 11 was the first spacecraft to fly past Saturn. The spacecraft made its closest approach at just 20,900 kilometres (13,000 miles) away.

Date: 12 November 1980
Activity: Voyager 1 became the second spacecraft to fly past Saturn. During its flyby Voyager 1 discovered three new Saturnian moons: Prometheus, Pandora and Atlas.

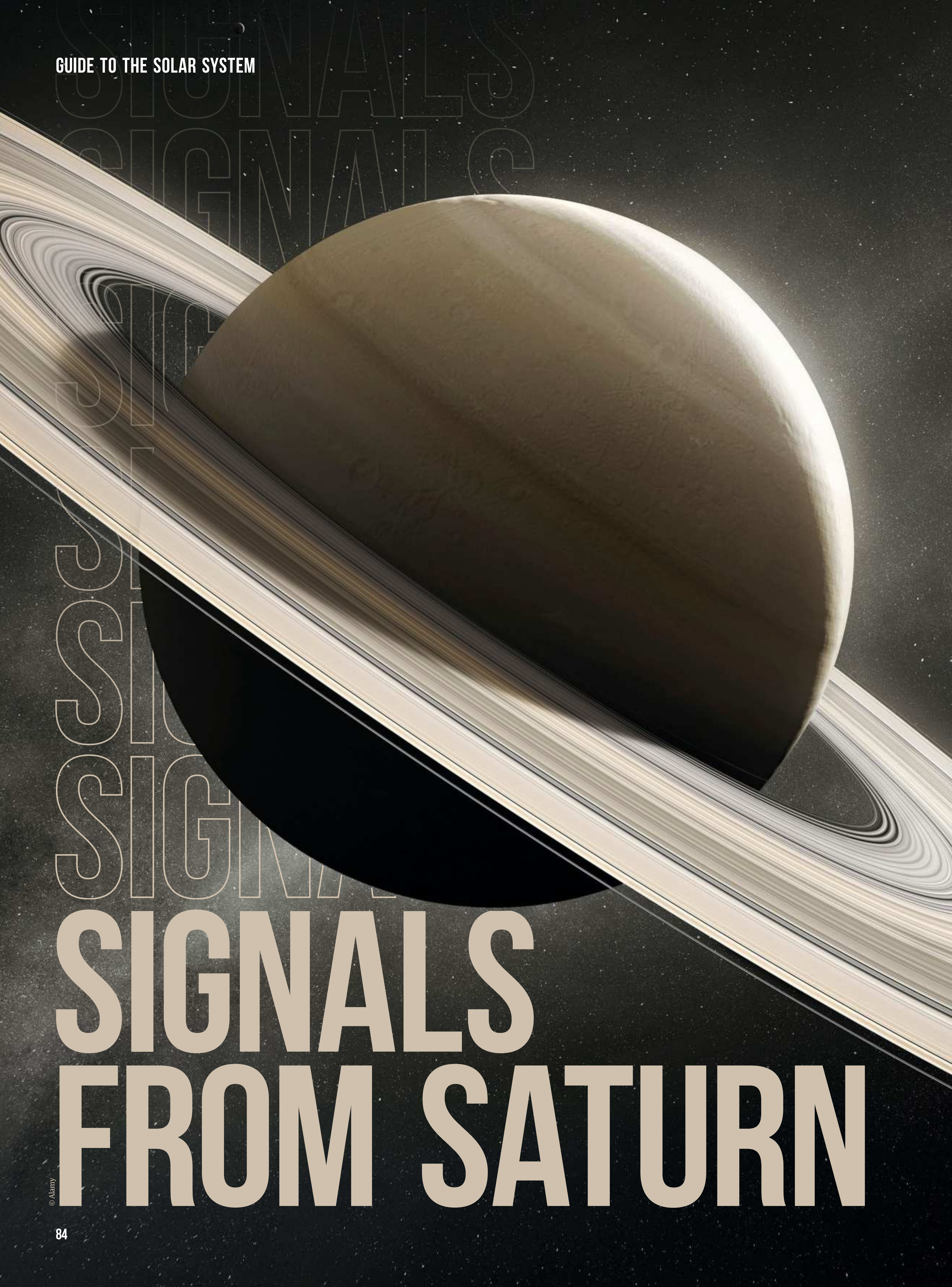
Date: 26 August 1981
Activity: Voyager 2 became the third spacecraft to fly past Saturn. Data collected by Voyager 2 suggested that Saturn's A ring was only about 300 metres (984 feet) thick.

Date: 1 July 2004
Activity: NASA's Cassini became the first spacecraft to complete an orbit of Saturn.

Date: 26 October 2004
Activity: NASA's Cassini achieved its first close encounter with Saturn's moon Titan. The spacecraft came within 1,200 kilometres (750 miles) of the moon's surface.

Date: 14 January 2005
Activity: The ESA's Huygens probe successfully landed on the surface of Titan, making it the first spacecraft to make a soft landing on the surface of another planet's moon.

Date: 15 September 2017
Activity: Cassini's mission comes to a dramatic end when it performs a planned plunge into Saturn's atmosphere, beaming back valuable data to the last second.



SIGNALS FROM SATURN

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An unusual signal from the ringed planet's moon Rhea now has a possible explanation

Reported by Nigel Watson

When NASA's Cassini spacecraft flew past Rhea, Saturn's second-largest moon, it detected an unexpected and puzzling change in the ultraviolet radiation reflected from its surface. The data from Cassini's flybys has led to a range of speculation and possibilities. Dr Amanda Hendrix, an expert in ultraviolet spectroscopy of planetary surfaces at the Planetary Science Institute in California, said that they noticed a dip in the spectrum and wondered if it was caused by some type of water ice. It was certainly an intriguing puzzle.

The signal was detected by the Cassini craft that was launched from Cape Canaveral on 15 October 1997. After seven years of travel it reached Saturn on 1 July 2004, and in total it orbited the planet for over 13 years. When it became very low on fuel it was decided to end the mission, and to avoid biological contamination of the planet or its moons it was deliberately sent into Saturn's atmosphere, where it burnt up on 15 September 2017.

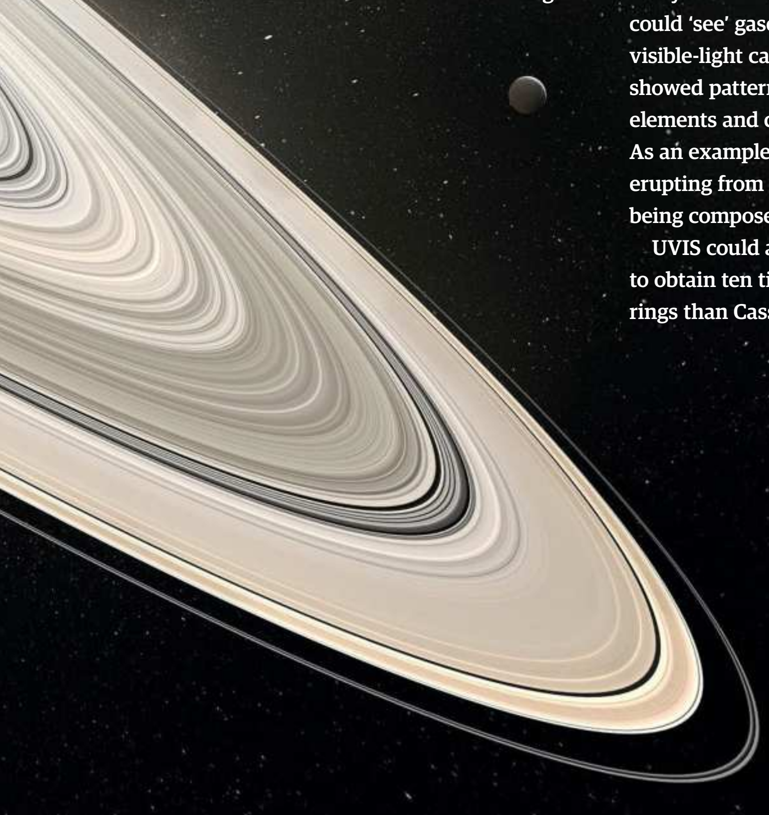
Cassini is one of the largest ever interplanetary probes to be built, weighing 2,150 kilograms. It carried the European Space Agency's (ESA) Huygens lander probe, which it sent towards Titan, Saturn's largest moon, on 25 December 2004. After 21 days of travel Huygens finally entered Titan's atmosphere on 14 January 2005, and once on its frozen surface it transmitted data for 72 minutes until Cassini went out of range.

Since then scientists have researched this information to investigate the atmosphere of Titan and its geology. They made several important discoveries, including the fact that the levels of methane increased as the craft descended, whereas the amount of nitrogen remained constant. The presence of methane is exciting because it could be produced by micro-organic life, but ESA scientists think it is more likely large amounts of liquid methane are trapped under the surface ice and released into the atmosphere by cryovolcanism.

Besides the ill-fated Huygens, Cassini carried a large array of instruments to study Saturn and its moons. Some of these measured its magnetosphere and the presence of dust particles, and infrared, visible and ultraviolet images were captured using cameras and spectrographs. It was the Ultraviolet Imaging Spectrograph (UVIS) science package that detected the puzzling findings sent back from Rhea. The UVIS included a two-channel system for studying far and extreme ultraviolet light in wavelengths of 55.8 to 190 nanometres (nm).

The light reflected from planetary objects passed through the four UVIS telescopes into a spectrograph, where it was split into its component wavelengths. These wavelengths, invisible to the human eye, were able to show information and images of the night side atmospheres of Saturn and Titan. Hendrix, who analysed this data, said that this ability meant it could 'see' gases that were not seen by Cassini's visible-light cameras. This ultraviolet light also showed patterns that revealed the chemical elements and compounds in the Saturn system. As an example, it identified a plume of material erupting from the south pole of Enceladus as being composed of water.

UVIS could also use an occultation technique to obtain ten times more detail of Saturn's rings than Cassini's visible-light cameras. This



RHEA BY NUMBERS

1672
Year Giovanni Cassini discovered Rhea

1847
Year it was named by John Herschel

1,528 KM
Diameter of Rhea

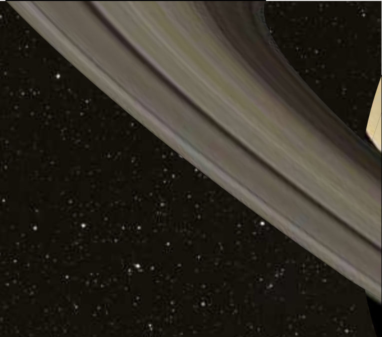
-174°C
Maximum surface temperature

-220°C
Minimum surface temperature

1.233
times denser than liquid water

4.518
Days it takes to orbit Saturn

527,068KM
Average distance from Saturn



SATURN'S FAMILY PORTRAIT

The sixth planet from the Sun has a distinctive ring system and at least 82 moons

1 Titan

The giant of the Saturn family, it is bigger than our own Moon and a little bigger than the planet Mercury, having a diameter of 5,149.46 kilometres (3,200 miles). It takes roughly 16 days to orbit Saturn and permanently presents one side towards the planet.

There is the exciting possibility that primitive life forms might exist in the liquid water ocean that lies beneath the moon's surface. Unlike any other moon in the Solar System it has a substantial atmosphere that is mostly composed of nitrogen and methane.

2 Rhea

The second-largest moon. The surface is mainly composed of water ice and it has an ice mantle. Its chemical composition and evolutionary history are very like that of Dione. They both have ice cliffs that are caused mainly by tectonic strains that fractured the moons' surfaces. The side of Rhea that always faces away from Saturn has two large impact craters: the 500-kilometre (311-mile) diameter Mamaldi basin and the 360-kilometre (224-mile) diameter Tirawa basin. The impact scar of Tirawa overlaps Mamaldi, indicating that it is geologically younger. The unusual far-ultraviolet radiation from Rhea detected by Cassini, centred near 184 nanometres in the electromagnetic spectrum, was probably caused by hydrazine. How or where it comes from still remains a mystery.

3 Dione

Although it's smaller than Rhea, it has a higher mass density, which is 1.48 times that of liquid water, indicating it has a silicate rock core surrounded by ice. It might even have a liquid salt water ocean beneath its surface. An outstanding feature of the moon is a bright pattern of icy cliffs that were seen as long, wispy streaks in the images from the Voyager probes.

It has a landscape of craters, tectonic fractures and a tenuous exosphere. Some of the craters are 100 kilometres (62 miles) across, and there is a variety of heavily and lightly cratered plains.

1

3

2

What is hydrazine?

Hydrazine is a colourless, inorganic liquid that is highly combustible and smells like ammonia. It has similar properties to water in terms of density, surface tension, viscosity and freezing point. It is very toxic and can cause burns and serious damage to vital organs. It is often used to propel thruster motors on spacecraft. They work by hydrazine being exposed to a catalyst, causing the release of heat and gas that is directed out of the engine's nozzle.

involved UVIS locking onto a bright star and recording how the ultraviolet light changed when the rings of Saturn or a planetary body passed between them.

The perplexing dip in the far-ultraviolet from Rhea, centred near 184nm, is outlined in Dr R. Mark Elowitz' PhD thesis *Far-Ultraviolet Spectroscopy of Saturn's Moons Rhea and Dione*. In it he notes that data from Rhea and Dione showed a weak absorption feature near 184nm, and that as early as 2008 it was found that Phoebe presented similar readings. At the time, various ice mixtures of water, tholins, carbon, kerogen and poly-HCN could not explain this feature. Observations of Mimas, Enceladus and Tethys have also revealed absorption spectra in the same region of the spectrum.

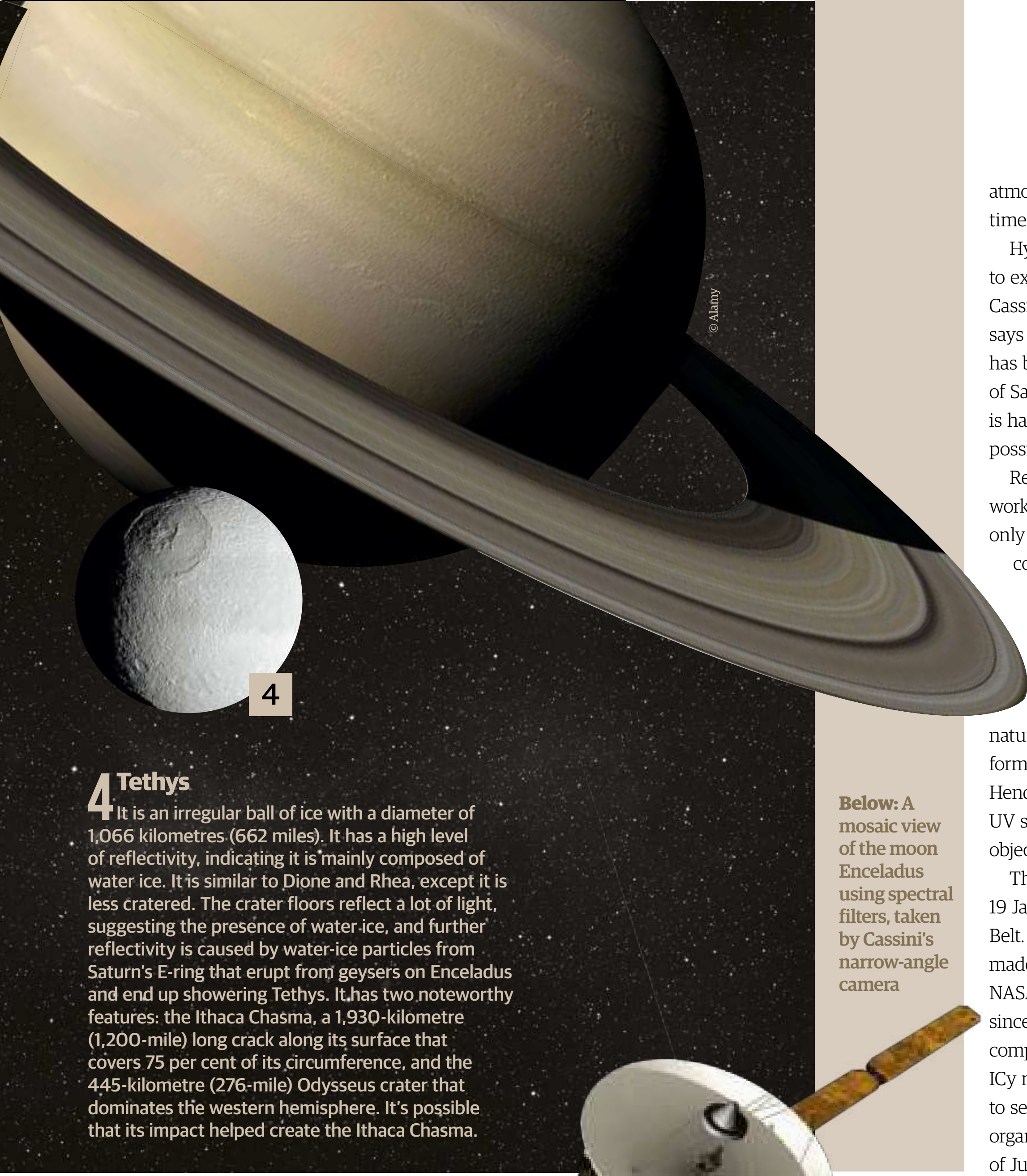
To explain the Rhea signal, scientists decided the best route to an answer was to compare the spectra collected by Cassini to the spectra of thin-ice measurements in the laboratory. The far-ultraviolet data was extracted from targeted flybys of Rhea in 2007, 2010 and 2011 using datasets that completely filled the moon's surface and provided the highest signal-to-noise spectra. Elowitz, who was one of the team members, says: "Over 20 modelled spectra of different chemical species of interest to studies of icy moons in the outer Solar System were compared with the Cassini observational data, with only two chemical species representing a good fit to the observed reflectance spectra. Those two chemical species included simple chloromethane molecules and hydrazine monohydrate. To determine the most likely of these two chemical species to exist in the upper surface ice layer on Rhea, the different sources and sinks of each chemical compound were explored, including the various chemical pathways that could lead to their production."

Considering the two possible chemical compounds, it was determined that simple chloromethane compounds are least likely to be the answer. As Elowitz notes: "It would require the presence of a deep subsurface ocean under the ice shell of Rhea. It is unlikely the chloromethane compounds or salt derivatives of these compounds could migrate upwards through tiny cracks or fissures over hundreds of kilometres to the surface."

The only other possible source of chlorine is via exogenic delivery by chondritic asteroids or micrometeoroids throughout the history of Rhea. If these simple chloromethane compounds were scattered over Rhea in this manner, they would produce by-products on the surface ice of Rhea. These chemical by-products were not found, so this possibility had to be ruled out.

That left the researchers having to explain why hydrazine monohydrate was detected. One immediate possibility was that the Cassini craft itself produced the hydrazine, as it was equipped with a 132-kilogram tank of hydrazine that fuelled its 16 attitude and small trajectory thruster motors.

Professor Nigel Mason, head of the School of Physical Sciences at the University of Kent and a co-author, along with Elowitz and Hendrix, of the science paper *Possible Detection of Hydrazine on Saturn's Moon Rhea*, says: "We looked at spectra of other moons, like Dione and Tethys, since if the



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4

4 Tethys

It is an irregular ball of ice with a diameter of 1,066 kilometres (662 miles). It has a high level of reflectivity, indicating it is mainly composed of water ice. It is similar to Dione and Rhea, except it is less cratered. The crater floors reflect a lot of light, suggesting the presence of water ice, and further reflectivity is caused by water-ice particles from Saturn's E-ring that erupt from geysers on Enceladus and end up showering Tethys. It has two noteworthy features: the Ithaca Chasma, a 1,930-kilometre (1,200-mile) long crack along its surface that covers 75 per cent of its circumference, and the 445-kilometre (276-mile) Odysseus crater that dominates the western hemisphere. It's possible that its impact helped create the Ithaca Chasma.

Below: A mosaic view of the moon Enceladus using spectral filters, taken by Cassini's narrow-angle camera

atmosphere and is deposited over geologically long timescales on Rhea's upper ice layer."

Hydrazine therefore remains the prime candidate to explain the absorption signature seen in the Cassini far-ultraviolet spectral data, though Hendrix says we still need to figure out why this feature has been observed on some of the other moons of Saturn. In her view it indicates that this process is happening throughout the Saturn system, and possibly elsewhere.

Regarding future studies, Mason says: "In future work we are looking at spectra of other moons, not only to search for hydrazine, but to look for other compounds. The UV spectral database is used to look at other planets and moons, so we are exploring the chemistry of Jovian moons in preparation for the JUICE mission, and hopefully data from the Juno mission now it has been extended. Due to their volcanic nature, sulphur compounds are expected to be formed on those moons, so we are looking for these. Hendrix is also on the New Horizons team with the UV spectrometer, so data from Pluto and Kuiper Belt objects is being analysed as well."

The New Horizons space probe was launched on 19 January 2006 to explore Pluto and the Kuiper Belt. It swung past Jupiter in February 2007 and made its closest approach to Pluto on 14 July 2015. NASA's Juno space probe has been orbiting Jupiter since 5 July 2016, where it has been studying the composition of the planet. The ESA's JUICE (JUpiter ICy moons Explorer) is scheduled for launch in 2022 to search for possible habitable environments for organic molecules in the icy crusts and ocean layers of Jupiter's moons Ganymede, Callisto and Europa.

signal was present on all moons it might suggest we should look for a common source, for example spacecraft fuel contamination of the spectrometer. The data from Tethys showed no signal, and we looked at other spectra to check for contamination and if the spacecraft motors were firing during or before observation to leave a 'plume' of hydrazine."

The spacecraft's own thrusters seemed a very likely culprit, but they had to be ruled out because they were never fired while Cassini made its flybys of Rhea. And, as Mason points out, hydrazine fuel would have contaminated data gained from other moons and not just showed up when it looked at Rhea.

Elowitz explains that if there is ammonia on the icy surface of Rhea, it could produce hydrazine "by irradiation from high-energy particles originating from Saturn's magnetosphere". However, he continues: "An alternative explanation is that hydrazine is produced on Titan from irradiation of ammonia present on its surface and/or atmosphere. The hydrazine then escapes from Titan's

THE LAUNCH OF CASSINI AR SCAN HERE

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The data from these missions might well help us further with the study of Saturn's system and the mysterious presence of hydrazine.

To investigate the matter further, Elowitz, in his PhD thesis, proposes that future space probes should be equipped with infrared and ultraviolet spectrometers to examine the surface of Rhea and the similar icy moons of Saturn. Cassini's UVIS instrument could be improved by employing a hyperspectral imaging system. Each pixel in the multi-layered sensor would obtain spatial and spectral information. The far-ultraviolet spectrum data received by each pixel would identify chemical compounds by reference to their reflective properties, and the whole instrument would be able to create detailed geochemical maps of selected areas of interest. "The detailed spectral maps would be used to characterise the spatial variability of the abundance of hydrazine monohydrate or chloromethane molecules, which could not be performed using the previous Cassini UVIS data due to limitations resulting from low signal-to-noise," notes Elowitz.

The use of advanced spectrometers with higher sensitivities could be used to examine the upper layers of Rhea, Dione and Tethys for the presence of hydrazine monohydrate or chlorine molecules, and it would be great to send landing craft to these moons. The Curiosity rover carried mass spectrometers and gas chromatographs that detected dichloromethane on Mars, so any future surface landers on the icy moons should be equipped with similar equipment to help verify the existence of hydrazine or chloromethane. Certainly there is plenty more to learn and understand about this fascinating signal.

Above: Technicians were dwarfed by the huge Cassini-Huygens craft as they tested it in 1996

Nigel Watson
Space science writer
Nigel has written extensively about science and technology, in particular about extraterrestrial contact. He is the author of four books on alien life.

CASSINI SPACECRAFT

1 High-gain antenna
The four-metre (13-foot) wide antenna sent data back to Earth, and variations in the signal helped to study Saturn's atmosphere. The central low-gain antenna had a wider, less powerful range.

2 Magnetometer (MAG)
Two magnetometers were mounted on a boom to detect the strength and distribution of Saturn's magnetic field and its influence on its moons.

3 Radio and Plasma Wave Science (RPWS)
Three ten-metre (33-foot) long antennae were used to detect radio waves and plasma in Saturn's magnetosphere.

4 Remote-sensing pallet
Included wide-angle and narrow-angle cameras along with instruments to study Saturn's electromagnetic spectrum.

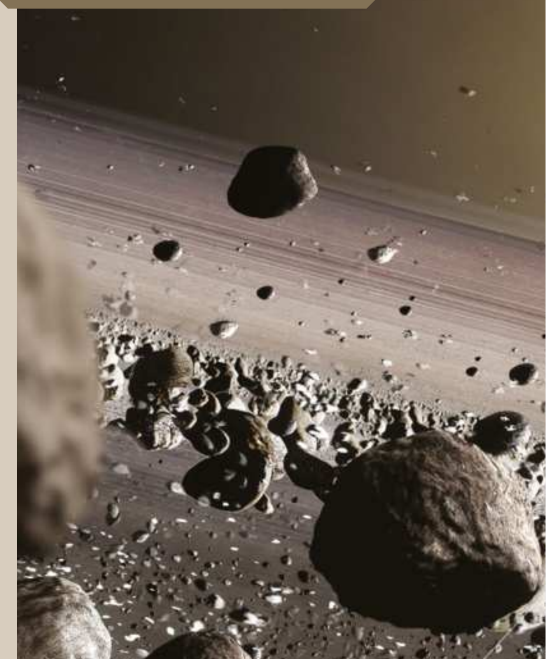
5 Engines
One main engine and an unused back-up engine were used for velocity and trajectory changes. 16 thrusters were used for smaller manoeuvres.

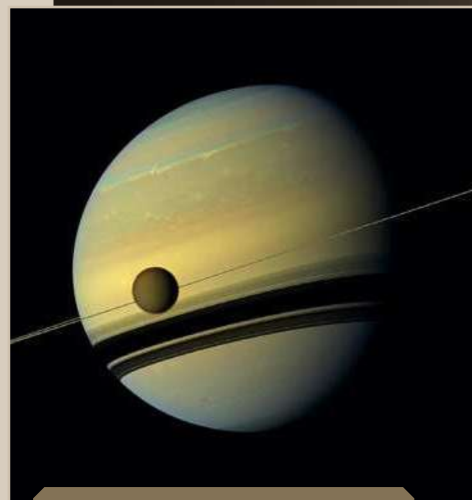
6 Radioisotope thermoelectric generators (RTGs)
Through the decay of plutonium-238, the three RTGs supplied electrical power to the spacecraft and its instruments.

7 Huygens Titan probe
The 318-kilogram craft carried six scientific instruments to the surface of Titan, where it transmitted data back to the orbiting Cassini craft.

8 Fields and Particles pallet
Featured instruments to study cosmic dust, magnetic fields, plasma and gaseous components surrounding Saturn.

9 Radar bay
Using a multi-beam sensor, this was designed to map the surface of Titan and other moons of Saturn and study Saturn's rings.





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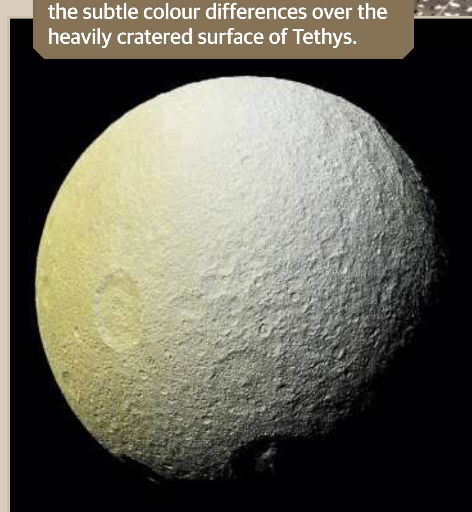
A mosaic of images taken by Cassini's wide-angle camera – using red, green and blue spectral filters – showing Saturn, its rings and Titan.



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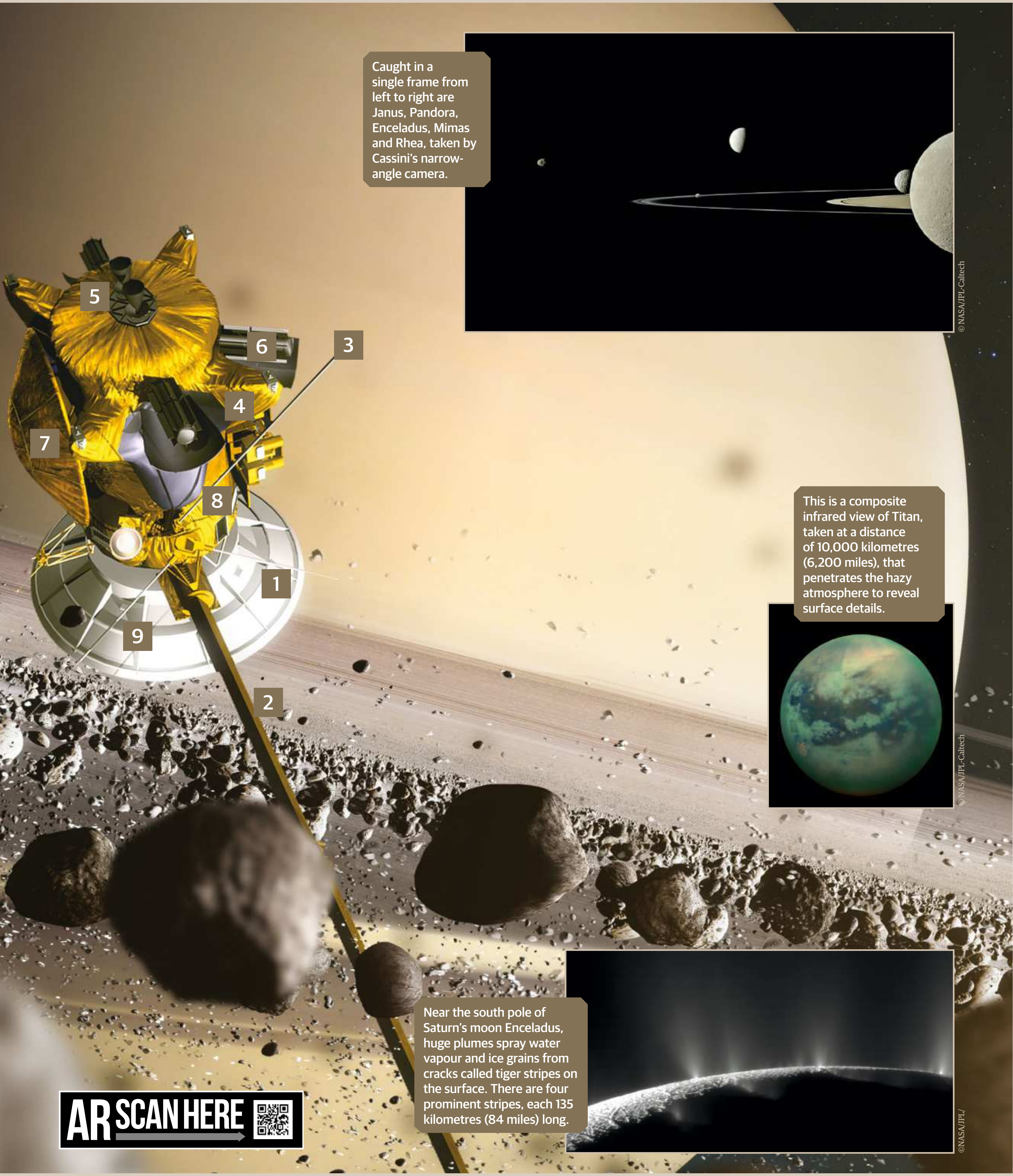
A combination of infrared, green and ultraviolet filters were used to show the subtle colour differences over the heavily cratered surface of Tethys.



Caught in a single frame from left to right are Janus, Pandora, Enceladus, Mimas and Rhea, taken by Cassini's narrow-angle camera.

© NASA/JPL-Caltech

This is a composite infrared view of Titan, taken at a distance of 10,000 kilometres (6,200 miles), that penetrates the hazy atmosphere to reveal surface details.

© NASA/JPL-Caltech

Near the south pole of Saturn's moon Enceladus, huge plumes spray water vapour and ice grains from cracks called tiger stripes on the surface. There are four prominent stripes, each 135 kilometres (84 miles) long.

©NASA/JPL/

MOON PROFILE
TITAN

Saturn's moon is a harsh, uninhabitable world, yet has uncanny similarities to our home planet

Titan is one of the most intriguing moons in our Solar System. From the outside astronomers see a ball of golden-orange haze, but it's what's hiding beneath this atmosphere that intrigues – a freezing world with bodies of liquid. Planetary scientists are fascinated by Titan and its unusual contents.

Titan, the largest moon of Saturn and second-largest moon in the Solar System behind Jupiter's Ganymede, is an icy ball that stretches out to almost 5,150 kilometres (3,200 miles) in diameter, nearly 50 per cent wider than the Earth's Moon. Due to Saturn's position, which is around 1.4 billion kilometres (870 million miles) from the Sun, nine-times farther than Earth's average distance, its satellite Titan receives sunlight that is 100-times fainter than the light on Earth. This freezing world may be one that is inhospitable for humans, but there are bodies of liquid present on the surface. These observations have been the subject of many studies throughout the decades.

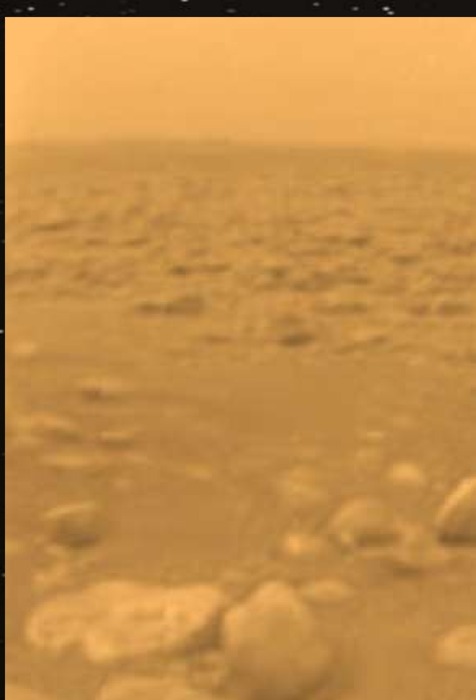
Although there are many interesting moons in the Solar System, Titan is the most Earth-like: it has an atmosphere and it is rocky, but also has bodies of liquid on the surface with a rain cycle replenishing them. All of this happens on a moon that has a surface temperature of minus 179 degrees Celsius (minus 290 degrees Fahrenheit); there obviously isn't water on Titan as that would have been frozen. These lakes, rivers and seas are filled with liquid hydrocarbons such as methane and ethane. These complex molecules are capable of existing as a liquid in such a cold temperature.

As for the atmosphere – in fact, Titan is the only moon with a thick atmosphere in the Solar System – it has an atmospheric pressure 60 per cent greater than that of the Earth. This would feel the same as swimming 15 metres (50 feet) below the surface in an ocean on Earth. This atmosphere is comprised mostly of nitrogen, with a whopping 95 per cent. Around five per cent is methane and the extremely small remainder is carbon-rich compounds. This provides the orange haze that is seen from afar.

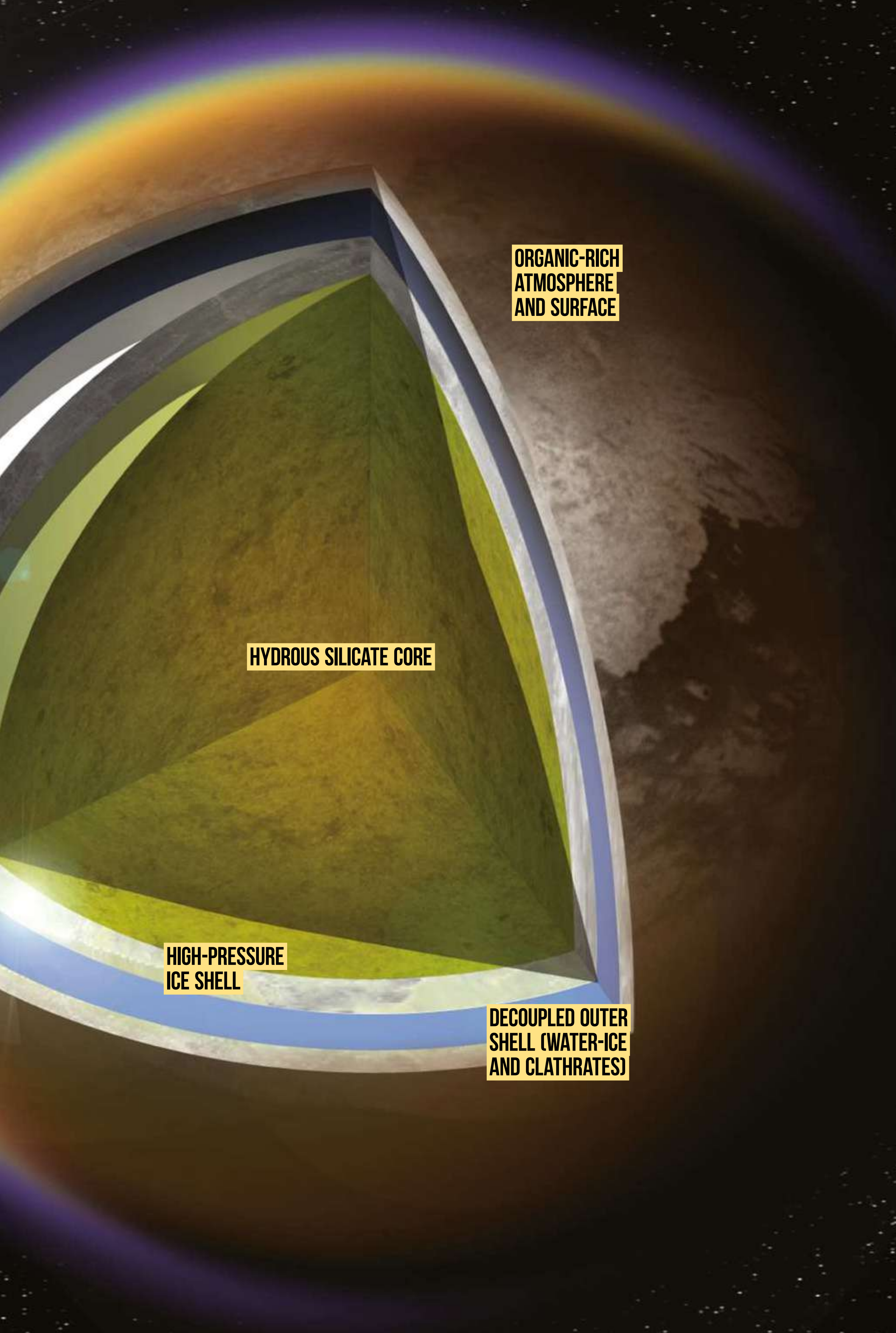
The presence of an atmosphere and surface liquid means there is a cycle of evaporation and condensation, creating clouds of methane ice and cyanide gas and precipitation in the form of methane rain. A moon with a weather cycle is unusual, and astronomers are amazed at how the Earth's water cycle can be applied to a distant, alien world.

There is a mystery about Titan that astronomers can't seem to explain with any conviction, and that's what is replenishing Titan's atmosphere. It is known that sunlight breaks up methane at the top of the moon's atmosphere, and scientists are wondering what is bringing more methane into the atmosphere in its place. One suggestion has been volcanic activity. The presence of volcanoes would be yet another amazing similarity between Titan and our home planet.

> "TITAN HAS BODIES OF LIQUID ON THE SURFACE WITH A RAIN CYCLE REPLENISHING THEM"



Huygens sent back images of the Titanian surface to Cassini



ATMOSPHERIC COMPOSITION

95%
NITROGEN

5%
METHANE

+

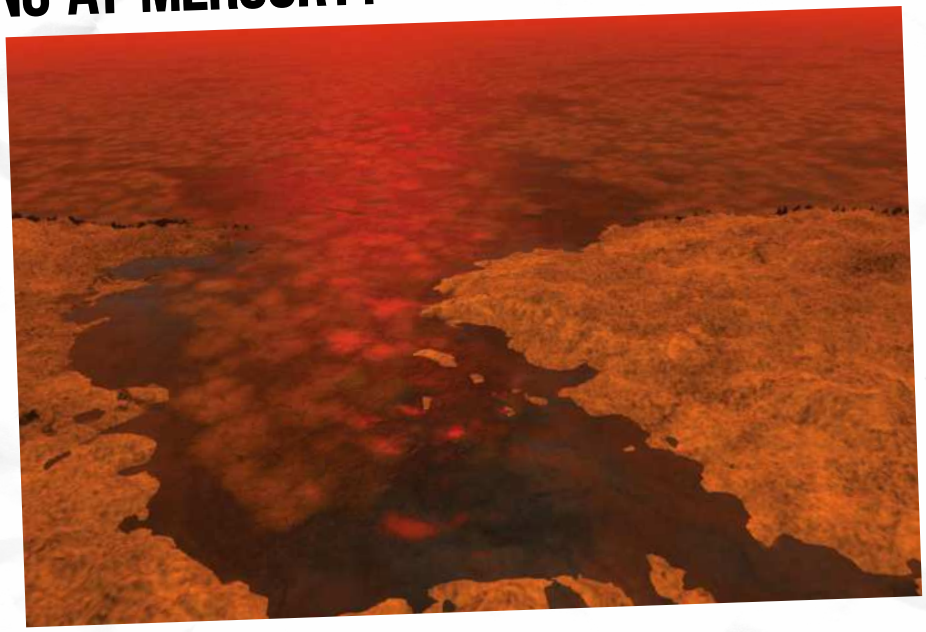
TRACES OF CARBON-RICH COMPOUNDS

WHAT'S BEEN HAPPENING AT MERCURY?

UNDERSTANDING THE ATMOSPHERE

Titan's atmosphere is an enigma. Ever since its discovery astronomers have been trying to explain how such a dense atmosphere and surface liquid arose and were preserved for millions of years. "Because Titan is the only moon in our Solar System with a substantial atmosphere, scientists have wondered for a long time what its source was," says Dr Kelly Miller, a research scientist at Southwest Research Institute in San Antonio, Texas, United States. "The main theory has been that ammonia ice from comets was converted, by impacts or photochemistry, into nitrogen to form Titan's atmosphere. While that may still be an important process, it neglects the effects of what we now know is a very substantial portion of comets: complex organic material."

But how is it replenished? Well, Miller believes this can be explained by 'cooking' organic materials brought to Titan via comets or other primitive objects during the moon's conception. When these materials are cooked, gases are released, and this is what is maintaining the levels of methane on Titan.



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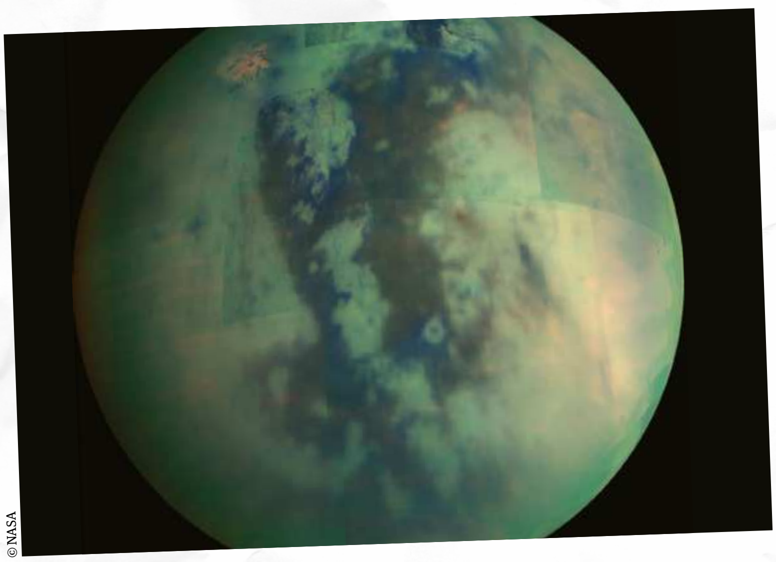


© NASA

CHANGING SEASONS

Much like seeing the seasons change from summer to winter on Earth, scientists have spotted signs of the changing seasons on Titan using valuable data from NASA's now-deceased Cassini spacecraft. Using pictures of the moon's northern hemisphere, Rajani Dhingra – a doctoral student in physics at the University of Idaho in Moscow, United States – and her team have seen rainfall on the north pole. The rainfall also provides the first indication of the beginning of a summer season.

"The whole Titan community has been looking forward to seeing clouds and rains on Titan's north pole, indicating the start of the northern summer, but despite what the climate models had predicted, we weren't even seeing any clouds," said Rajani Dhingra. "People called it the curious case of missing clouds."

Now that these images have been acquired and analysed the case of Titan's seasons has become a little bit clearer, courtesy of Cassini and its Visual and Infrared Mapping Spectrometer instrument. The spacecraft's near-infrared capabilities allow it to peer inside the atmosphere and observe this rainfall. Compared to Earth's yearly cycle of four seasons, a season on Titan lasts seven Earth years.

DUST STORMS SWEEPING THE SURFACE

If you didn't already think that Titan was a harsh enough environment, Cassini also spotted giant dust storms sweeping across the moon's surface. This observation raises intrigue as astronomers try to work out what is generating this powerful gust around the equatorial region.

"Titan is a very active moon," says Sébastien Rodriguez, an astronomer at the Université Paris Diderot, France. "We already know that about its geology and exotic hydrocarbon cycle. Now we can add another analogy with Earth and Mars: the active dust cycle in which organic dust can be raised from large dune fields around Titan's equator."

In the same way the weather changes with the seasons on Earth, the same occurs on Titan. In this case, when the Sun crosses Titan's equator massive clouds are formed in these tropical regions, creating powerful methane storms. This is what astronomers looking at this feature thought was occurring, but it turned out to be something completely different. After more modelling scientists discovered that these are actually clouds of organic molecules raised from the dune, and therefore the first observation of a dust storm on Titan.

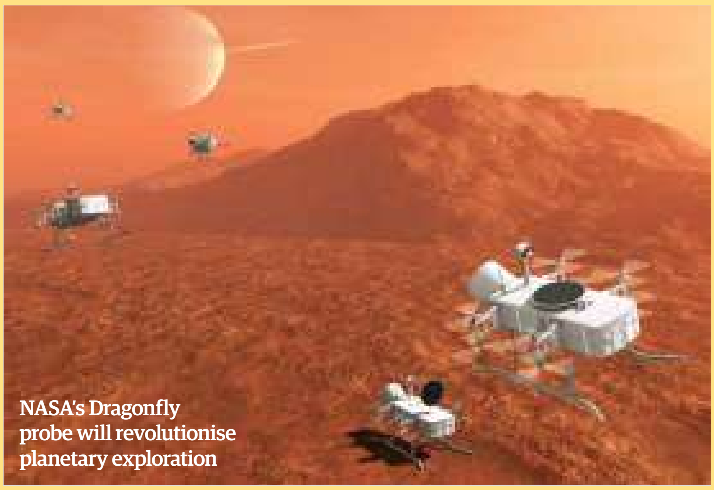
x3 images © NASA/JPL-Caltech

MISSION TO TITAN

Titan isn't exactly a nearby neighbour we can pop to and see how it's doing, like Mars. When Earth and Saturn are closest to each other they are still 1.2 billion kilometres (746 million miles) apart. This means visits to Titan in the past have been few and far between. The first probe to visit the Saturnian system was NASA's Pioneer 11 in 1979, followed by Voyager 1 and 2 in 1980 and 1981 respectively. NASA's Voyager spacecraft were pivotal in making initial measurements of its physical properties such as mass, density, composition and so on. These observations caught the attention of many because of their irregularity.

The best spy sent to the Saturnian system, and in particular Titan, was the Cassini spacecraft and its accompanying Huygens lander, a collaborative mission between NASA, the ESA and ASI. Cassini-Huygens arrived at Saturn in July 2004 and made many observations of the moon before Huygens was released with the intention to burst through the hazy atmosphere of Titan and land on its surface. On 14 January 2005 Huygens made its successful descent onto Titan before its batteries died and communication ceased with Cassini. All observations of Titan after the fact were made by Cassini before it ended its mission by crashing into Saturn's atmosphere in September 2017. The data collected by Cassini is still providing new discoveries over a year after the mission's end.

There have been talks of sending more probes to the exciting moon using new and innovative ways. One idea that is in advanced discussion is the 'Dragonfly' lander, as part of NASA's New Frontiers program. The Dragonfly lander will not just sit on the surface like Huygens, it will be a dual-quadcopter drone capable of moving around Titan's thick and nitrogen-rich atmosphere. This would allow astronomers to get a closer look at different surface features and would allow more freedom in movement than a rover.



NASA's Dragonfly probe will revolutionise planetary exploration

© Adrian Mann

HUYGENS' DESCENT TO TITAN

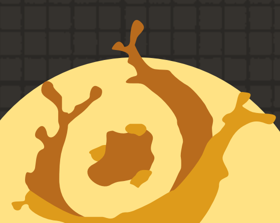
- **Time*:** 14 January 2005 10:13am UTC (11:13am CET)
  Activity: Huygens reaches the top of Titan's atmosphere.
- **Time:** 10:17am UTC (11:17am CET)
  Activity: Pilot parachute deploys, and a minute later the front shield is released and transmission to Cassini begins.
- **Time:** 10:32am (11:32am CET)
  Activity: Main parachute separates and drogue parachute deploys to guide Huygens to the right spot.
- **Time:** 11:57am UTC (12:57pm CET)
  Activity: The Gas Chromatograph Mass Spectrometer begins sampling the atmosphere before it touches the ground.
- **Time:** 12:34pm UTC (1:34pm CET)
  Activity: Huygens makes a successful touchdown on Titan.
- **Time:** 2:44pm UTC (3:44pm CET)
  Activity: Cassini stops collecting Huygens data, thus concluding its work, and at 3:14pm UTC the first data is sent to Earth.

*All times above are Earth Received Time - i.e. 67 minutes after the event has happened at the spacecraft

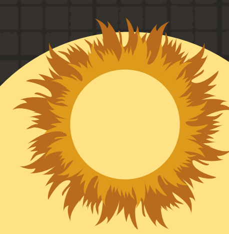
TITAN'S FACTS AND STATS

600 KM

Titan's atmosphere extends about 600 kilometres (370 miles) above its surface.



Data suggests there could be the presence of a liquid ocean beneath the surface.



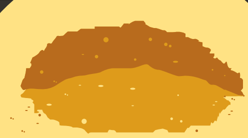
The conditions on Titan could become more hospitable when the temperature of the Sun increases 6 billion years from now.

2%

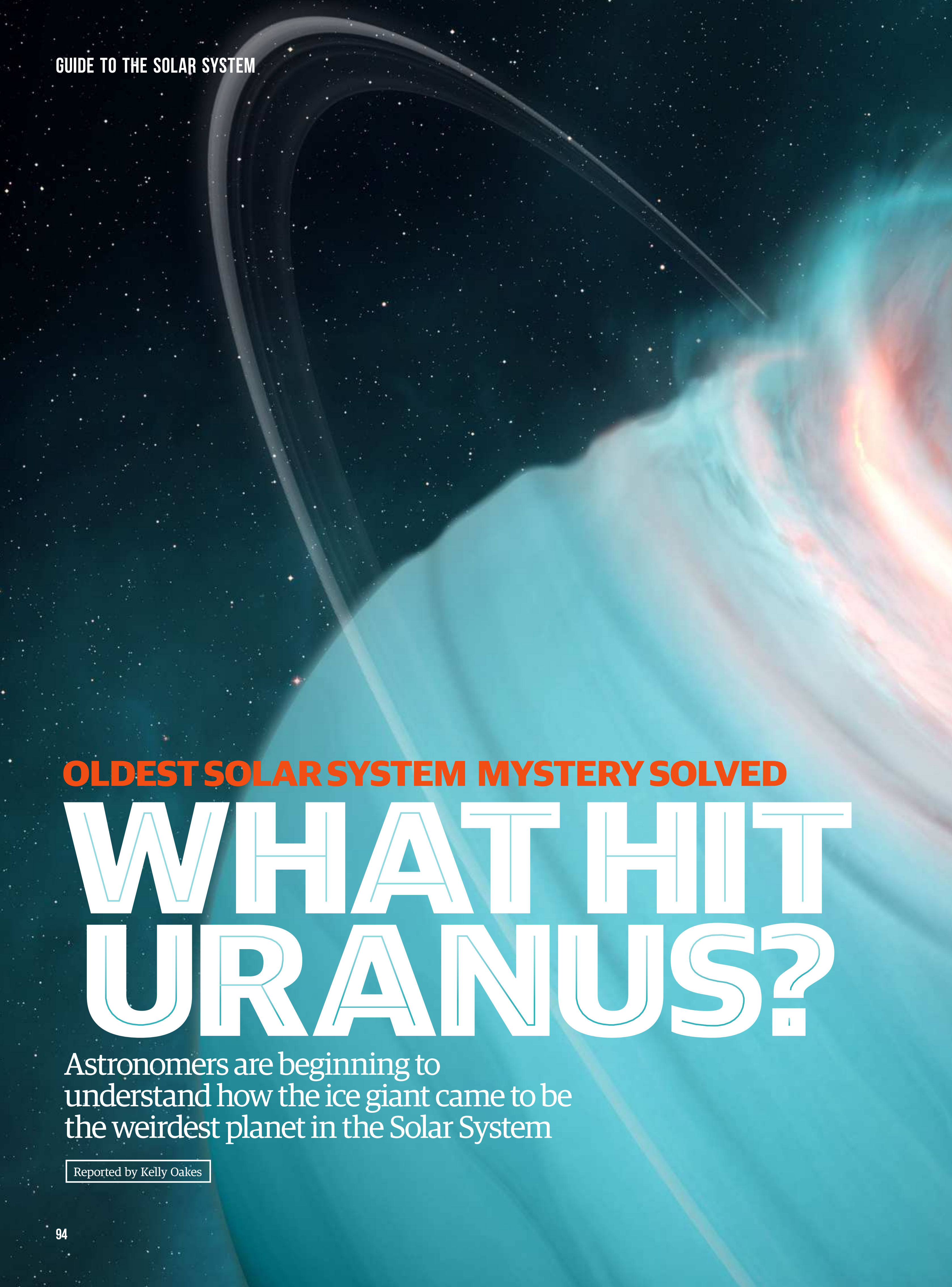
Jupiter's Ganymede is only two per cent larger, meaning there isn't much size between the two largest moons in the Solar System.

ESA's Huygens holds the record for most distant landing of a human-made probe.

Titan is tidally locked to Saturn, much like the Moon is to Earth, meaning only one side of Titan is facing Saturn at all times.



The 'sand' on Titan's dunes is composed of dark hydrocarbon grains that resemble coffee grounds.

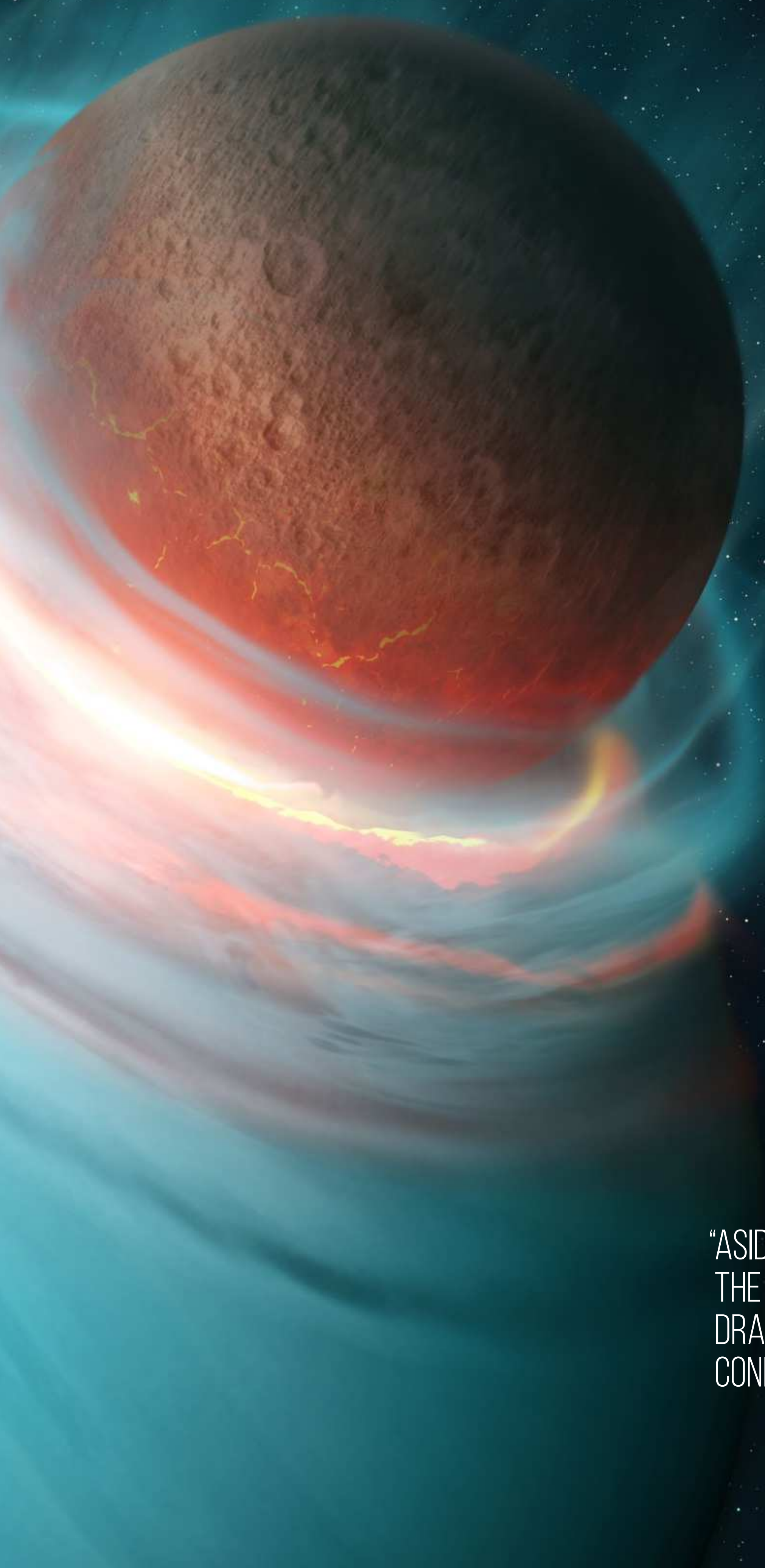


OLDEST SOLAR SYSTEM MYSTERY SOLVED

WHAT HIT URANUS?

Astronomers are beginning to understand how the ice giant came to be the weirdest planet in the Solar System

Reported by Kelly Oakes



The eight major planets in our Solar System are all mysterious in their own ways, but Uranus, seventh from the Sun, is particularly weird. The ice giant is tilted, its north and south poles where you would expect the planet's equator to be. Its magnetic field is off-centre. And though you'd expect an ice giant to be cold, Uranus is even colder than scientists think it should be. Now researchers are starting to unravel how it came to be this way.

Just like Saturn and Neptune, Uranus has a ring system. However, because the planet is tilted 98 degrees, its rings orbit the ice giant vertically instead of around its middle – for comparison, Earth is tilted 23 degrees, and Jupiter a mere three degrees. It also has plenty of moons, including five major ones and at least 22 other known satellites, which orbit the same way.

Aside from the moons and rings, Uranus' tilt also dramatically affects the conditions on the planet itself. The length of a day on Uranus changes a lot over the ice giant's orbit around the Sun. Each pole of Uranus spends around 42 Earth years pointing towards the Sun, while the other faces away, before they switch.

When one of the planet's poles is most directly pointing towards the Sun, called a solstice, only a small part of the planet near the equator experiences a day-night cycle, while that pole is bathed in light and the other in dark. As it orbits the Sun the planet gradually spins until eventually the other pole faces the Sun. In the middle, at the planet's equinoxes, the equator of the planet faces

"ASIDE FROM THE MOONS AND THE RINGS, URANUS' TILT ALSO DRAMATICALLY AFFECTS THE CONDITIONS ON THE PLANET ITSELF"

the Sun, and its day-night cycles are more similar to what we are used to on Earth.

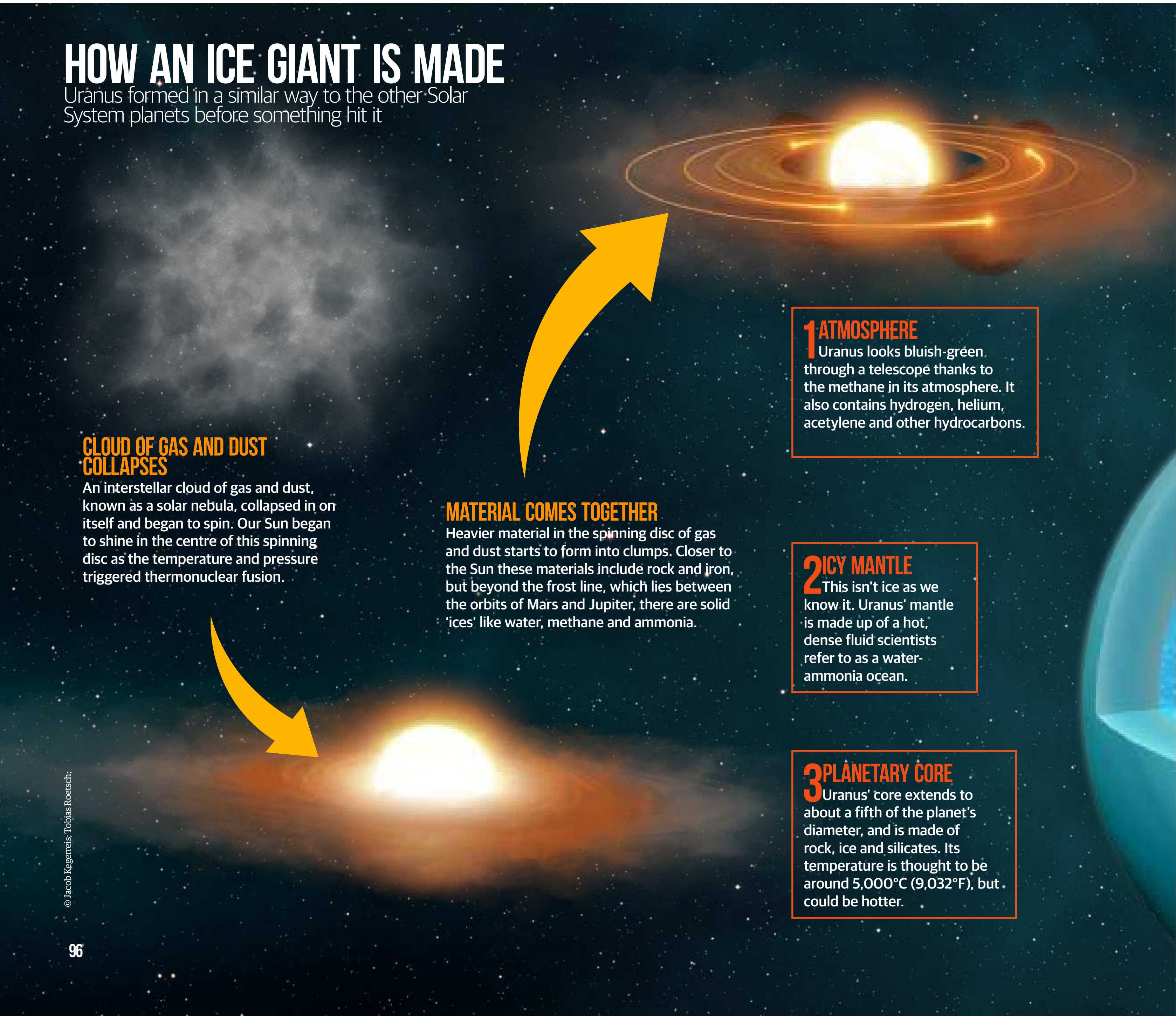
The planet itself looks pretty blank and featureless from a distance. When the Voyager 2 spacecraft came within 81,500 kilometres (50,600 miles) of the top of Uranus' atmosphere in January 1986 – the only time we have visited the planet – it saw a smooth, turquoise expanse. But this calm exterior belies stranger things underneath.

The planet's atmosphere is mostly made up of hydrogen, helium and methane, with some other hydrocarbons, too. The methane is what gives the planet its bluish-green hue, because the gas absorbs red wavelengths of light. Though it looks calm, the Hubble Space Telescope revealed that Uranus has an active weather system with strong winds, bright clouds and even aurorae. "It's very hard to see them because the exterior is so boring; it's hard to tell what's going on," says Jacob Kegerreis, a PhD student in computational astrophysics at the University of Durham.

Voyager 2 sent back thousands of images and plenty of scientific data from Uranus. The spacecraft pinned down the length of time the planet takes to rotate as 17 hours, 14 minutes. It revealed the spectacular detail of the previously known rings around the planet, and discovered two new ones. As well as this the spacecraft spotted 11 previously unknown moons orbiting the planet and found evidence of geological activity on the five largest: Miranda, Ariel, Umbriel, Oberon and Titania.

Perhaps the strangest thing Voyager 2 discovered about Uranus was its strangely wonky magnetic field, tilted not at the same angle as the planet but instead at 59 degrees, and not appearing to originate from the planet's centre. This means the strength of the magnetic field in each hemisphere of the planet is different – compare that to the magnetic field strength on Earth, which is strongest at the north and south poles and weakest at the equator, and you start to understand how peculiar it is. Another as yet unexplained mystery of the planet is how cold it is. The lowest temperature recorded

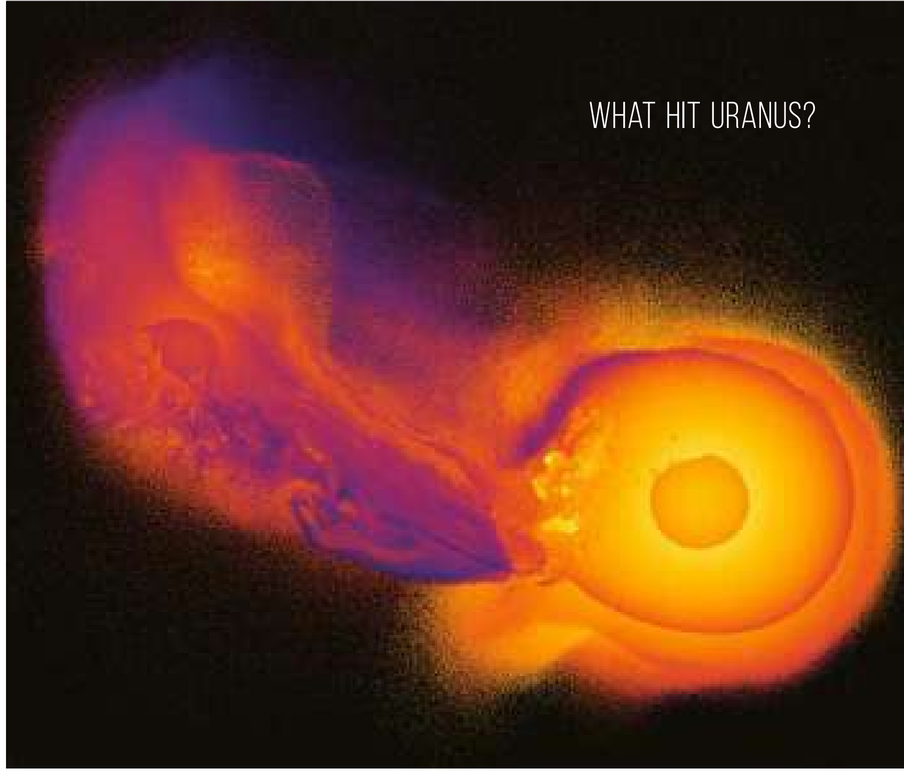
> "HUBBLE REVEALED THAT URANUS HAS AN ACTIVE WEATHER SYSTEM WITH STRONG WINDS, BRIGHT CLOUDS AND EVEN AURORAE"



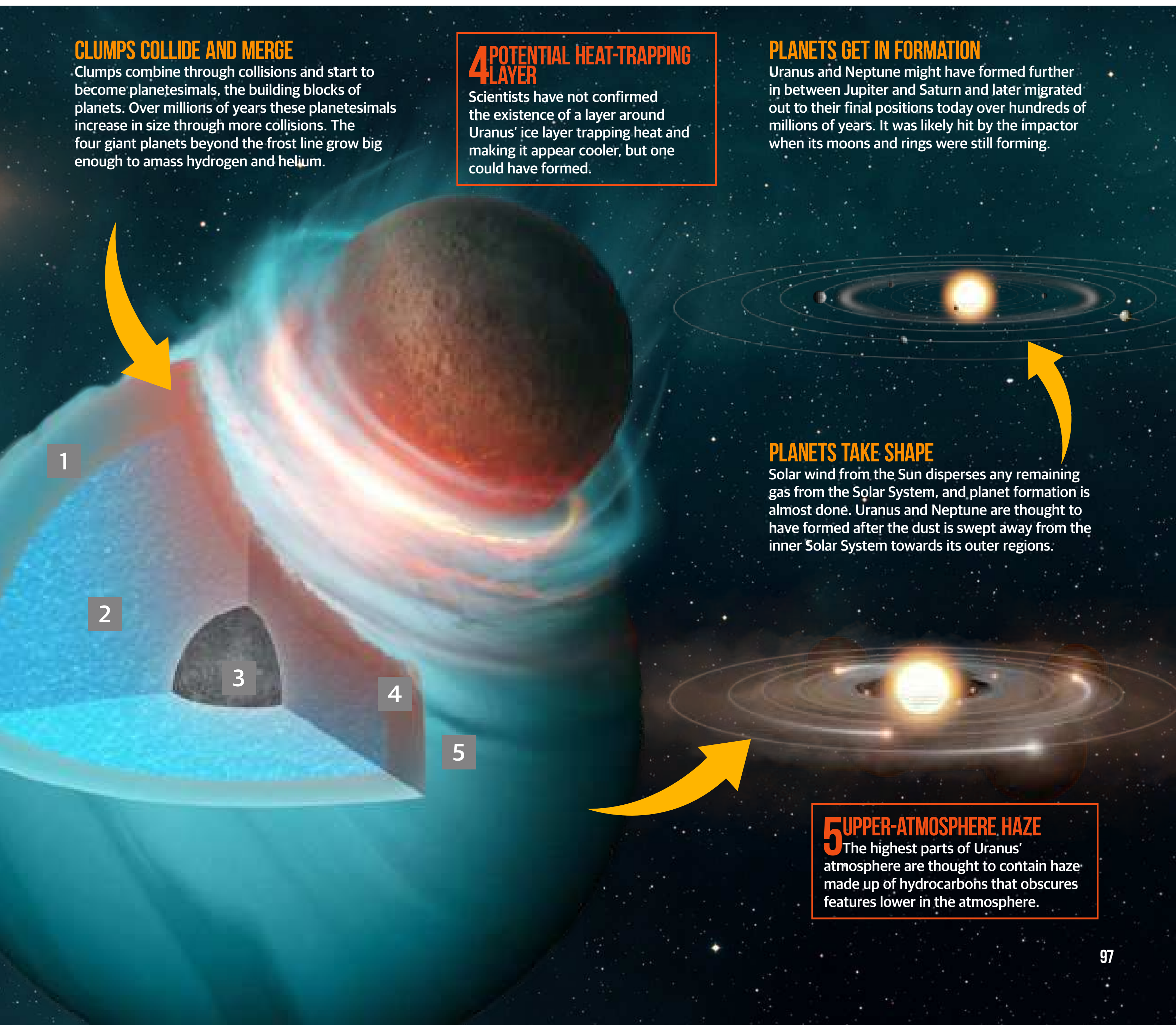
© Jacob Kegerreis; Tobias Roetsch;

on Uranus is −224.2 degrees Celsius (-371.56 degrees Fahrenheit). Other planets in our Solar System radiate more heat from their centres than they get from the Sun, but Uranus barely gives out any.

The answer to both of these mysteries might lie in what happened when Uranus became tilted. Planets are born out of discs of debris that circle nascent stars. When Uranus was formed it was likely spinning not too far off centre in much the same way as other planets in the Solar System. But new star systems in the process of forming are violent, hectic places. As well as the bodies that we know as planets today, there would have been potentially tens or hundreds of protoplanets - planets in a very early stage of formation, typically made of ice and rock - flying around the early Solar System. Once the initial debris disc around the Sun had disappeared, blown away by solar wind or cobbled together into other planets, these



Right: High-resolution simulations of a giant impact on Uranus, tilting the planet to the angle we see today



CLUMPS COLLIDE AND MERGE

Clumps combine through collisions and start to become planetesimals, the building blocks of planets. Over millions of years these planetesimals increase in size through more collisions. The four giant planets beyond the frost line grow big enough to amass hydrogen and helium.

4 POTENTIAL HEAT-TRAPPING LAYER

Scientists have not confirmed the existence of a layer around Uranus' ice layer trapping heat and making it appear cooler, but one could have formed.

PLANETS GET IN FORMATION

Uranus and Neptune might have formed further in between Jupiter and Saturn and later migrated out to their final positions today over hundreds of millions of years. It was likely hit by the impactor when its moons and rings were still forming.

PLANETS TAKE SHAPE

Solar wind from the Sun disperses any remaining gas from the Solar System, and planet formation is almost done. Uranus and Neptune are thought to have formed after the dust is swept away from the inner Solar System towards its outer regions.

5 UPPER-ATMOSPHERE HAZE

The highest parts of Uranus' atmosphere are thought to contain haze made up of hydrocarbons that obscures features lower in the atmosphere.

THE IMPACTOR

Simulations mean we can make an educated guess at what hit Uranus

NOT QUITE A PLANET

Uranus' impactor was likely a protoplanet that never accumulated enough mass to form into a planet in its own right.

TWICE THE SIZE OF EARTH

Simulations show that an object would need to be twice the size of Earth, if it struck Uranus with a glancing blow, to cause the tilt.

EMBEDDED IN THE PLANET

The rock and ice from the impactor is likely to have become part of the planet itself, or its moons, after the collision.

ROCK AND ICE

The impactor that hit Uranus was probably made up of rock and ice, some of which would have become incorporated into the planet on impact.

protoplanets would have become less stable and potentially ended up on collision paths with their fully grown siblings.

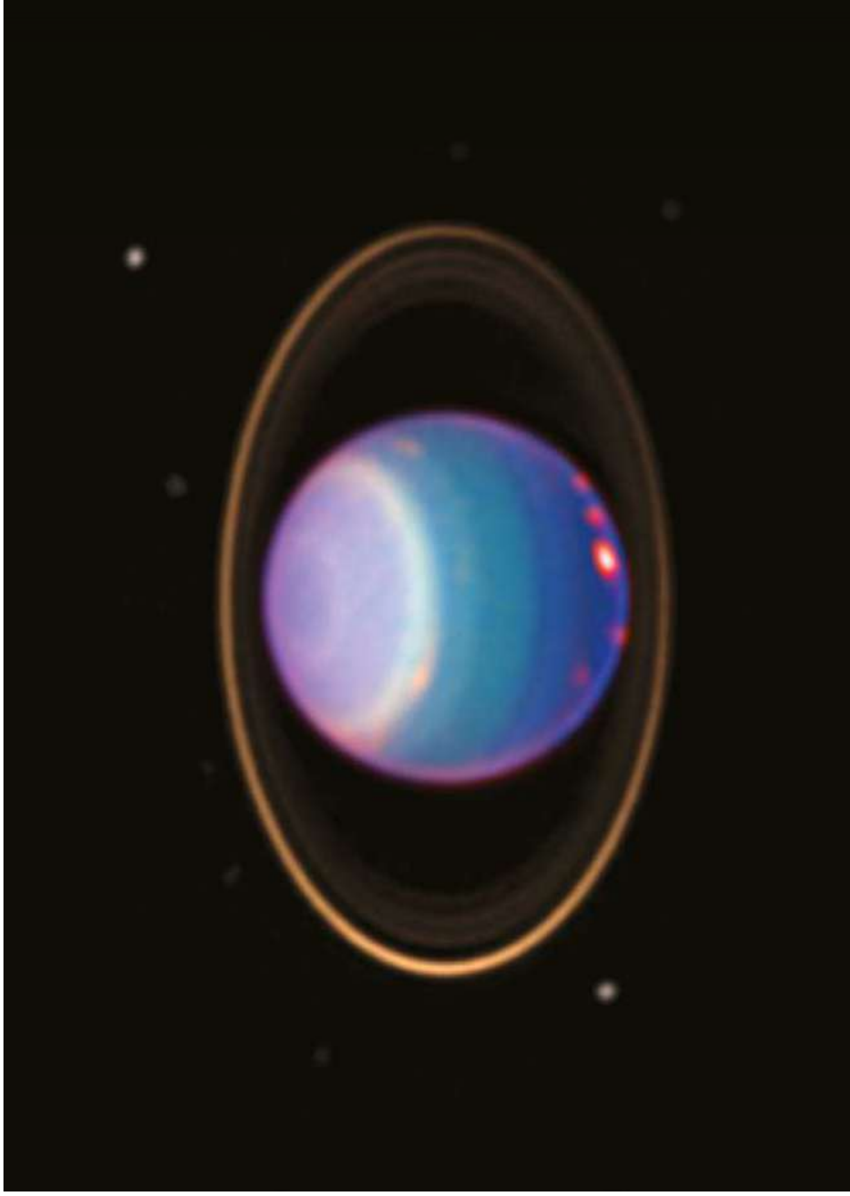
A protoplanetary hit job is the leading theory. "The giant-impact scenario is still the leading hypothesis to explain the high obliquity of Uranus," says Nadine Nettelman, a planetary scientist at the University of Rostock in Germany. Scientists think that as well as being responsible for the tilt of Uranus, giant impacts are to blame for other Solar System phenomena, including Earth's own Moon and Saturn's rings.

The trouble is we've never seen one of these impacts first hand, and we can't invent a time machine to go back to the early Solar System to check the hypothesis. Instead, researchers are using supercomputers to simulate these sorts of collisions and get to the bottom of what might have happened to Uranus. "We have millions of particles that we put down in our computer and we tell the computer simulation how those particles behave," says Kegerreis, who is part of a project using the technique, called smoothed-particle hydrodynamics, to investigate the giant planet. The researchers input information about how gravity works, what pressure the materials would be under, their density and temperature. "And then we just let those particles smash into each other and evolve the physics as the simulation does," says Kegerreis, "and see where they go."

The latest simulations, presented in a talk at the American Geophysical Union's annual conference last year, show that the impactor could have been an object twice the size of Earth. The object - likely a protoplanet left over from the formation of the Solar System - striking a grazing blow on Uranus would have been enough to knock it off-kilter, but not so violent as to make it lose the atmosphere that we still see surrounding the planet today.

Another finding from the simulations might explain why Uranus is so cold all of the time: debris from the impactor could have made a thin shell around the planet's ice layer, sealing in the inner heat. Nettelman, who published a paper suggesting the existence of such a 'thermal boundary layer' in 2016, says that this layer "prevents heat flow from escaping the deep interior". But it's too early on to rule out all other options when it comes to what hit Uranus; there's a chance the impactor could have been a smaller object in certain circumstances, for instance. If the planet was already tilted by the time an Earth-sized protoplanet hit it, this could have been enough of an extra push to give it the extreme tilt we see today.

The mass could have been bigger as well. "That would obviously be able to knock it over just as easily," says Kegerreis. "But the bigger you make the impact, the less likely it is for that to exist in terms of what would have been flying around the early



"THE BIGGER YOU MAKE THE IMPACT, THE LESS LIKELY IT IS FOR THAT TO EXIST IN TERMS OF WHAT WOULD HAVE BEEN FLYING AROUND"

ACOB KEGERREIS

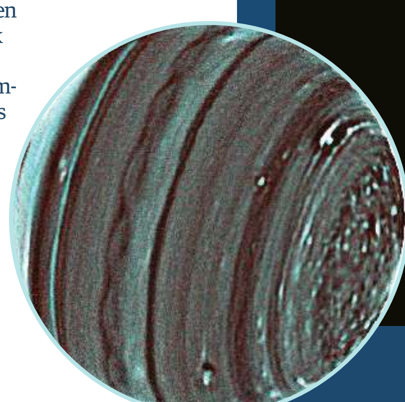
Solar System." There may be remnants of whatever hit Uranus embedded within the planet itself. In the simulations the researchers saw that an impactor could have left lumps of rock inside the planet. These might even be what's causing the ice giant's magnetic field to be tilted strangely and off-centre.

The moons could also provide clues about the impactor. The fact that the major moons of Uranus orbit around the planet's equator suggest that they were either formed from the debris left over after the impact or, if they were already in the process of forming when Uranus was hit, were dragged over when the planet was destabilised.

For his part, Kegerreis says the team is spoilt for choice about what to use the simulations to investigate next. They may look in more detail into what could have caused Uranus' lumpy, lopsided magnetic field, or probe how giant impacts can mix up and change the atmosphere of ice giant planets in general. "We've only just scratched the surface of what we can do with these big simulations," he says.

Above: This false-colour image by Hubble shows bright clouds in the planet's atmosphere in orange

Below: An infrared image of Uranus taken by the Keck II telescope shows storm-like features and clouds



HUBBLE WATCHES THE ICE GIANT'S WEATHER

Words by **Meghan Bartels**

IN COOPERATION WITH SPACE.com

If you don't like your local weather, perhaps you would prefer the atmosphere on Uranus or Neptune – and the Hubble Space Telescope has an update on each planet's current conditions.

The telescope regularly checks in on the two outer planets to see what's happening in their atmospheres, and last autumn Hubble captured incredible images of clouds on both worlds.

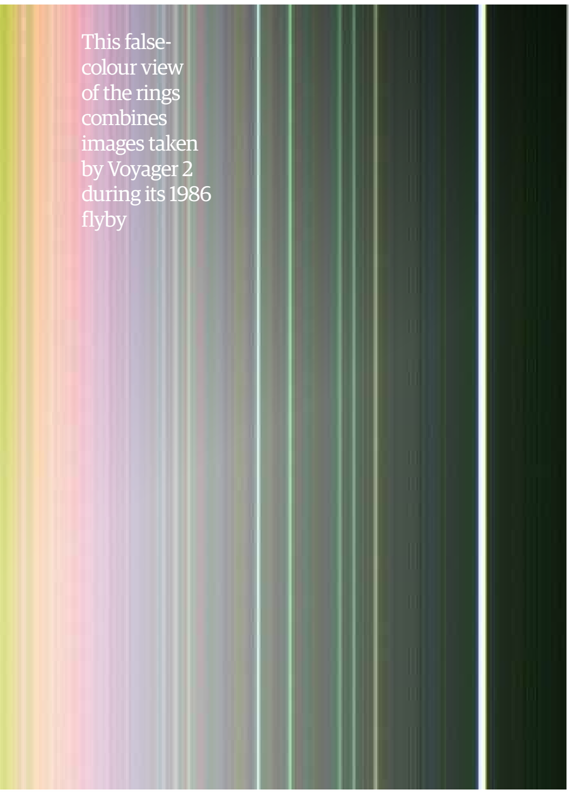
Uranus is currently deep into its summer season, and that shows in the giant, white cloud covering the planet's north pole, which currently points towards the Sun. As scientists have watched the Uranian summer progress – a season on this distant, giant world lasts 21 Earth years – they have seen this massive cloud grow even bigger. The large polar cap is accompanied by a smaller, bright cloud of methane ice.

On Neptune, where seasons last for 41 Earth years, it's winter in the northern hemisphere. That hemisphere is currently sporting a massive dark storm that stretches about 11,000 kilometres (6,800 miles) across.

Scientists aren't sure what phenomenon creates Neptune's dark storms, although the tempests seem to pop up about twice a decade and disperses within about two years. Researchers suspect that the storms creep upwards through the planet's atmosphere, lifting the ingredients of deeper layers of the atmosphere to the top.

Near the dark storm currently on Neptune, Hubble spotted another atmospheric feature: sparkling white 'companion clouds', which scientists have spotted around dark storms in the past. Astronomers suspect that these bright clouds are full of methane ice that's been rapidly pushed upwards and frozen.

Below: Uranus and Neptune as observed through Hubblea



This false-colour view of the rings combines images taken by Voyager 2 during its 1986 flyby

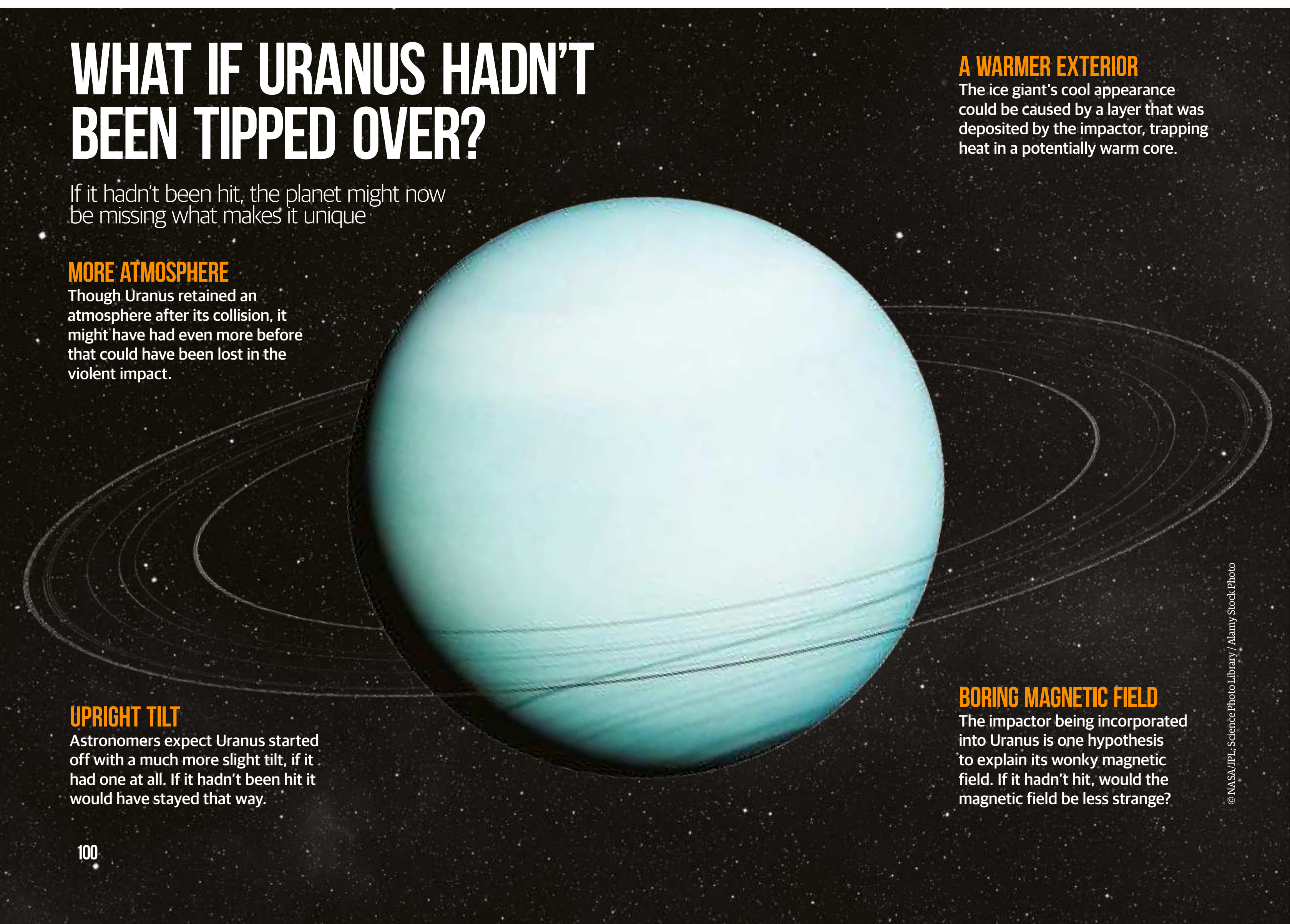
"WE REALLY NEED TO FIGURE OUT IF OUR UNDERSTANDING OF URANUS WOULD BENEFIT FROM A DEDICATED MISSION"

NADINE NETTELMAN

Despite the progress made in recent years, there are still many things left unexplained about Uranus. We still don't know how hot or cold the core of the planet is because we haven't pinned down the details of the possible thermal boundary layer that could be trapping in the heat. We know that Uranus and Neptune have similar magnetic fields, but we don't know why they have such different heat flows. Its icy sibling Neptune is also largely a mystery, having similarly only been visited by the Voyager 2 spacecraft in the summer of 1989. "Compared with pretty much all the other planets, apart from Neptune which is in the same position, an awful lot of the details we really don't know very well," confirms Kegerreis.

Thrusting Uranus and Neptune into the spotlight recently is the fact that a lot of the exoplanets astronomers have been finding outside of the Solar System are similar, at least in size, to the ice giants. In 2014 when Kepler announced the discovery of an incredible 715 new worlds in one go, roughly half of them were similar in size to Neptune. Learning more about the giant planets on our doorstep will make figuring out the details of faraway alien planets much easier.

Some researchers think the only way to really get to grips with Uranus will be a dedicated mission, and in recent years there have been several proposed missions to the ice giant. "I think the time is right, but the planning should not be hasted," says Nettelman. "We really need to figure out if our understanding of Uranus would benefit from a dedicated mission, or maybe more from a combined mission to both Uranus and Neptune." Combining theory and simulations with actual observations will help us get to the bottom of the mysteries hiding underneath Uranus' deceivingly calm exterior. Maybe it'll even teach us something about the whole universe of planets outside our Solar System, too.



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PLANET PROFILE

NEPTUNE

The isolated azure giant remains a relative mystery

Neptune is the eighth planet from the Sun. It was the first planet to have its existence predicted by mathematical calculations before it was actually seen through a telescope on 23 September 1846. Irregularities in the orbit of Uranus led French astronomer Alexis Bouvard to suggest that the gravitational pull from another celestial body might be responsible. German astronomer Johann Galle then relied on subsequent calculations to help spot Neptune via telescope. Previously, astronomer Galileo Galilei sketched the planet, but he mistook it for a star due to its slow motion. In accordance with all the other planets seen in the sky, this new world was given a name from Greek and Roman mythology: Neptune, after the Roman god of the sea.

Only one mission has flown by Neptune – Voyager 2 in August 1989 – meaning that astronomers have done most studies using ground-based telescopes. Today there are still many mysteries about the cool, blue planet, such as why its winds are so speedy and why its magnetic field is offset. While Neptune is of interest because it is in our own Solar System, astronomers are also interested in learning more about the planet to assist with exoplanet studies. Specifically, some astronomers are interested in learning about the habitability of worlds that are somewhat bigger than Earth.

Those that are closer to Earth's size are called 'super-Earths', while those that are closer to Neptune's size are 'mini-Neptunes'. However, there's some debate about those terms given that today's telescope technology doesn't make it possible to view how much atmosphere is on those planet types, making it difficult to make a distinction. Like Earth, Neptune has a rocky core, but it has a much thicker atmosphere that prohibits the existence of life as we know it. Astronomers are still trying to figure out at what point a planet becomes so large that it may pick up a lot of gas from the area, making it difficult or impossible for life to exist.

Neptune's cloud cover has an especially vivid blue tint that is partly due to an as-yet-unidentified compound and the result of the absorption of red light by methane in the planet's mostly hydrogen-helium atmosphere. Photos of Neptune reveal a blue planet, and it's often dubbed an ice giant, since it possesses a thick, slushy fluid mix of water, ammonia and methane ices under its atmosphere. It is roughly 17 times Earth's mass and nearly 58 times its volume. Neptune's rocky core alone is thought to be roughly equal to Earth's mass.

Despite its great distance from the Sun, which means it gets little sunlight to help warm and drive its atmosphere, Neptune's winds can reach up to 2,400 kilometres (1,500 miles) per hour – the fastest detected yet in the Solar System. These winds were linked with a large, dark storm that Voyager 2 tracked in Neptune's southern hemisphere in 1989. This oval-shaped, counterclockwise-spinning 'Great Dark Spot' was large enough to contain the entire Earth, and moved westward at nearly 1,200 kilometres (750 miles) per hour. This storm seemed to have vanished when the Hubble Space Telescope later searched for it. Hubble has also revealed the appearance and then fading of other dark spots over the past decade, and a new one was observed in 2016. It doesn't look like Neptune is finished with surprising scientists just yet.

AR SCAN HERE

Left: A Voyager 2 view of Neptune

"TODAY THERE ARE STILL MANY MYSTERIES ABOUT THE COOL, BLUE PLANET, SUCH AS WHY ITS WINDS ARE SO SPEEDY"

ATMOSPHERIC COMPOSITION

80%
HYDROGEN

19%
HELIUM

1.5%
METHANE

OVERALL COMPOSITION

25%
ROCK

60-70%
ICE

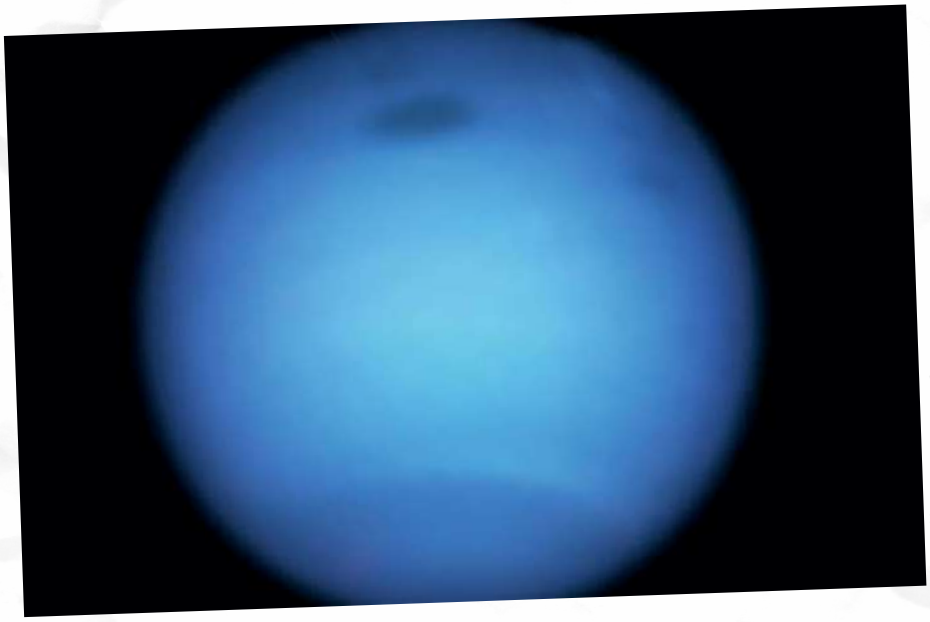
5-15%
HYDROGEN AND HELIUM

NEWS FROM NEPTUNE

A DARK STORM ON NEPTUNE MYSTERIOUSLY REVERSED

A dark storm on Neptune abruptly switched direction and started moving away from almost certain death, puzzling astronomers. NASA's Hubble Space Telescope first spotted the vortex in 2018. A year later, the storm began drifting southward towards Neptune's equator, following the path of several storms before it. Usually these dark spots on Neptune live for a few years before either vanishing or fading away. However, the storm mysteriously stopped moving south and made a sharp U-turn, drifting back northwards. At the same time, astronomers spotted a second, smaller dark spot on the planet. They theorise that this smaller 'cousin' may be a piece of the original vortex that broke off and drifted away.

Although Hubble has tracked similar storms on Neptune over the past 30 years, astronomers have never seen such unpredictable atmospheric behaviour. The 2018 storm, which was 7,403 kilometres (4,600 miles) across, is the fourth-darkest spot Hubble has tracked since 1993.



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NEPTUNE'S SMALLEST MOON HAS A VIOLENT PAST

Hippocamp is believed to have a diameter of about 34 kilometres (21 miles). The tiny moon circles in the same general neighbourhood as six moons discovered by Voyager 2 during the probe's flyby of Neptune in 1989. Hippocamp is just 12,000 kilometres (7,450 miles) inland to the largest and outermost of these other six, Proteus.

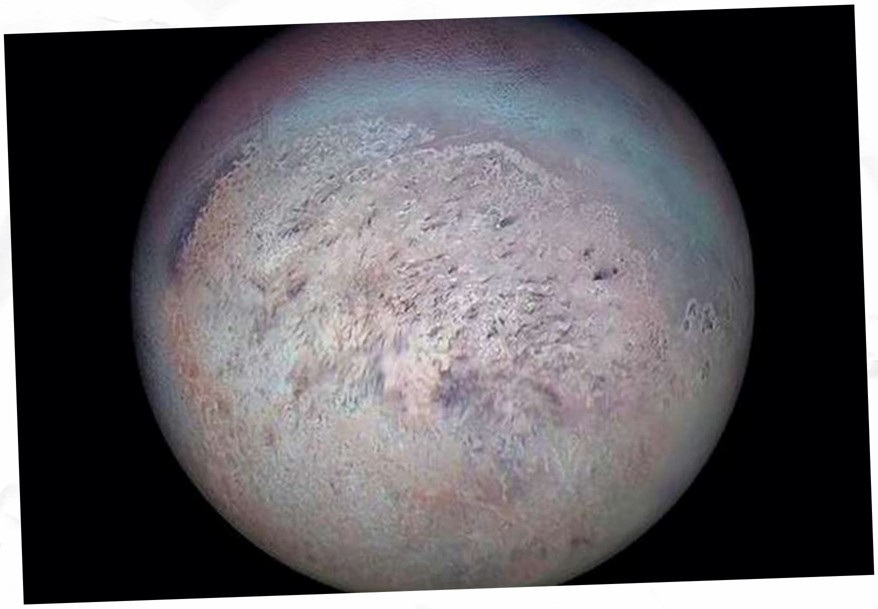
Like Earth's Moon, Proteus has been slowly spiralling away from its parent planet. So has Hippocamp, though at a much slower rate. About 4 billion years ago, Proteus was probably right next to Hippocamp and would have gobbled the smaller moon up. Scientists believe that Hippocamp was once part of its larger neighbour and likely coalesced from pieces of Proteus that were blasted into space by a long-ago comet impact.

NEPTUNE'S MOON TRITON HAS A RARE KIND OF ICE

Neptune's largest moon Triton boasts an uncommon icy mixture of carbon monoxide and nitrogen, which could help astronomers better understand the conditions of other distant alien worlds.

Using the Gemini Observatory in Chile and a high-resolution spectrograph called the Immersion Grating Infrared Spectrometer (IGRINS), a visiting instrument for Gemini, astronomers detected a distinct infrared signature on Triton, revealing a mixture of carbon monoxide and nitrogen frozen as solid ice. This finding helps explain seasonal atmospheric changes on Triton and how material is transported across the moon's surface via geysers.

The icy mixture detected on Triton could help explain the moon's iconic geysers, which are the dark, windblown streaks first observed by NASA's Voyager 2 spacecraft in the moon's south polar region. These distinct streaks are believed to be erupted material from an internal ocean, or an icy mixture that migrates around the surface in response to changing seasonal patterns of sunlight.



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WHEN TRITON CRASHED THE PARTY AT NEPTUNE

Neptune's original satellites may have been destroyed when its largest moon, Triton, entered the picture. The massive moon may have tossed some of the original satellites into the ice giant, kicked others out of orbit and swallowed up the rest, creating a new family that doesn't look much like those of other giant planets.

For years scientists have suspected that Triton wasn't part of Neptune's original collection of moons. The massive moon has a backward orbit and makes up over 99 per cent of all the mass orbiting the planet. They think it's a captured object whose orbit was circularised by debris discs created by impacts.

The moons of Jupiter, Saturn and Uranus are all well-behaved compared with Neptune's. The other three gas giants have a wealth of satellites – Jupiter has 79 to Neptune's 14 – travelling in nearly circular paths around their equators. While Triton's path is circular, it travels backwards compared with Neptune's rotation, and spins backwards too.

© NASA

EVOLUTION OF NEPTUNE

- **Date:** 23 September 1846
  Activity: Astronomer Johann Gottfried Galle viewed Neptune through a telescope for the first time
- **Date:** 10 October 1846
  Activity: Neptune's largest moon Triton was discovered
- **Date:** 25 August 1989
  Activity: NASA's Voyager 2 flew by Neptune and came within just 3,000 kilometres (1,860 miles) of the planet's north pole
- **Date:** 1 July 2013
  Activity: Neptune's smallest moon S/2004 N1 was discovered during an analysis of older Hubble images
- **Date:** 8 October 2013
  Activity: Neptune's 'lost' moon Naiad was spotted for the first time in 20 years. The tiny moon had remained unseen since the cameras on NASA's Voyager 2 spacecraft first discovered it in 1989.

NEPTUNE BY NUMBERS

165 EARTH YEARS
How long Neptune takes to complete an orbit of the Sun

-214°C
Average temperature on Neptune

14
The number of known moons of Neptune

28.3°
The angle of Neptune's tilt as it orbits the Sun

4.5 BILLION KILOMETRES
How far Neptune is from our Sun

7.6 BILLION SQUARE KILOMETRES
The surface area of Neptune

27x
How many times more powerful Neptune's magnetic field is than Earth's.

16 HOURS
The length of a day on Neptune

© SETI Institute

> "SCIENTISTS SUSPECTED TRITON WASN'T PART OF NEPTUNE'S ORIGINAL COLLECTION OF MOONS"

DWARF PLANET PROFILE
PLUTO

The dwarf planet in the realms of the Kuiper Belt is not just a barren ball of rock and ice

Pluto is arguably the most famous of all the dwarf planets, with many still fighting in its corner to get back its status as a planet. It resides in the darkest depths of the Solar System, the Kuiper Belt, 5.9 billion kilometres (3.7 billion miles) away from the Sun, which is roughly 40-times the Earth-Sun distance. The original member of the nine planets of the Solar System was discovered in 1930 by an American astronomer by the name of Clyde Tombaugh. Although Tombaugh discovered the dwarf planet, the credit for naming Pluto goes to an 11-year-old girl from Oxford, England, called Venetia Burney. She suggested that the then-planet be named after the Roman god of the underworld, which can't be far off the same conditions as the Kuiper Belt - dark, lonely and unbearably cold, with temperatures reaching as low as -240 degrees Celsius (-400 degrees Fahrenheit).

Its enormous distance from the Sun leads to Pluto having an equally enormous year - it takes 248 Earth years to complete one orbit. To put that into context, if Pluto completed an orbit this year, then when it started that orbit no one would have had a clue about Pluto, and French astronomer Charles Messier would have still been in the process of constructing the famous Messier Catalogue of deep-sky objects.

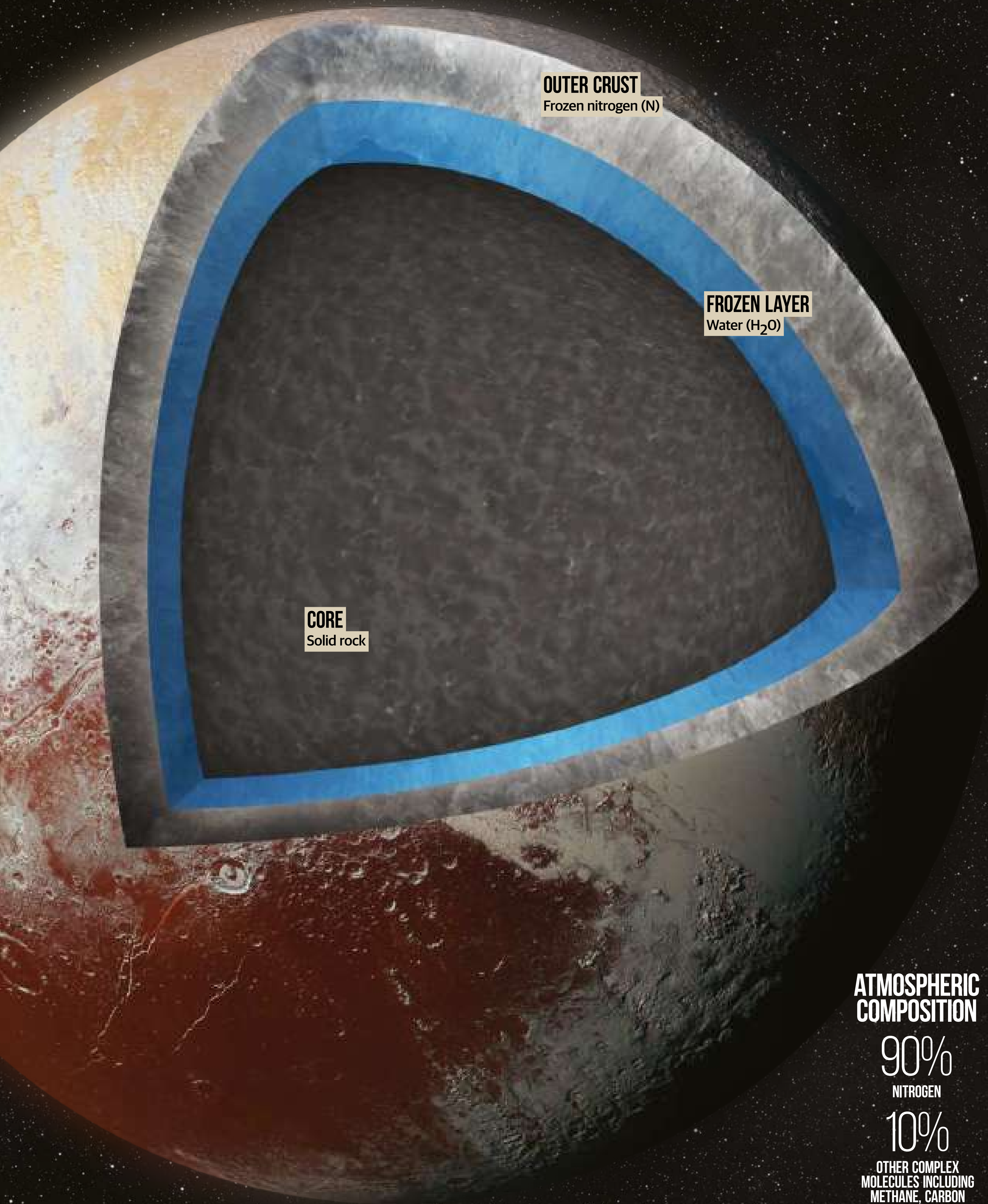
Pluto saw its declassification to a dwarf planet in 2006 when the International Astronomical Union defined the criteria of a planet, with Pluto just falling short. It is only a small world: it is roughly 2,400 kilometres (1,500 miles) wide, making it about two-thirds the size of the Moon and half the width of the United States. Although Pluto had been observed by many ground-based telescopes, and even NASA/ESA's Hubble Space Telescope, its true form and physical characteristics weren't apparent until it had its one-and-only flyby by NASA's New Horizons spacecraft, launched in 2006.

After the flyby in 2015 the surface of Pluto came into marvellous resolution, and many people of Earth marvelled at its beauty. "The complexity of the Pluto system - from its geology to its satellite system to its atmosphere - has been beyond our wildest imagination," says Alan Stern, New Horizons principal investigator from the Southwest Research Institute in Boulder, Colorado, United States. "Everywhere we turn are new mysteries."

When astronomers first observed the surface they noticed a host of mountains, valleys, plains and craters, but the plains of frozen nitrogen gas exhibit very few craters, meaning that there must be some sort of surface replenishment - possibly material spraying from a subsurface ocean. All of this was possible to see with Pluto's virtually nonexistent atmosphere that consists of molecular nitrogen, with traces of methane and carbon monoxide also having been detected.

Pluto has five known moons: Charon, Nix, Hydra, Kerberos and Styx. These moons were likely formed as the result of a collision between Pluto and an object of similar size billions of years ago. Charon is the largest of these moons and is about half the size of Pluto, making it the largest moon relative to its host. In fact, the Pluto-Charon double act can sometimes be referred to as a double planet system.

Left: Pluto and its main moon Charon compared against Earth



ATMOSPHERIC COMPOSITION

90%
NITROGEN

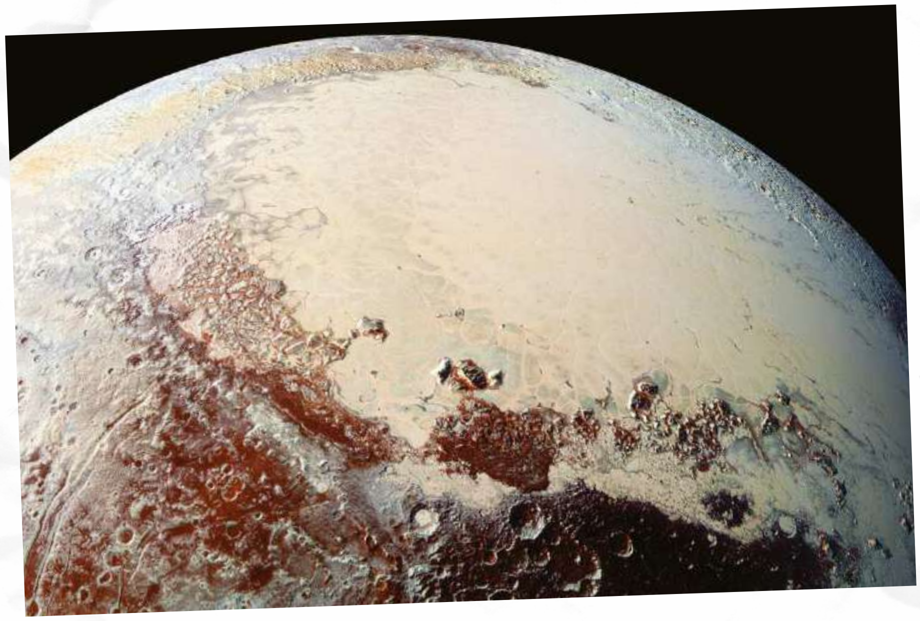
10%
OTHER COMPLEX MOLECULES INCLUDING METHANE, CARBON MONOXIDE AND MORE

PLUTO CATCH-UP

WARMING THE HEART OF PLUTO

When New Horizons flew past Pluto in 2015, it shattered perceptions of a dull, rocky ball and instead opened astronomers' eyes to the idea this could be an active world. On its flyby the spacecraft revealed a heart-shaped region in the northern hemisphere of the dwarf planet known as Tombaugh Regio. After studying data on this region, astronomers have found evidence for a subsurface ocean existing under the layer of nitrogen ice.

"This could mean there are more oceans in the universe than previously thought, making the existence of extraterrestrial life more plausible," says Shunichi Kamata of Hokkaido University in Japan. This study suggests that there is a layer of gas hydrates – ice-like solids composed of gases trapped in molecular water – that insulates that region of Pluto, which prevents freezing within its interior. Ocean worlds are an exciting area of research in the Solar System because it means that one of the fundamental needs for life is abundant beyond our home planet. It could mean that extraterrestrial life could exist elsewhere in the Solar System.



RE-OPENING THE PLANETARY DISCUSSION

29 April 2019 saw an informal vote about whether Pluto should be reinstated as a planet or remain a dwarf planet. This vote saw the inclusion of experts on the matter, including NASA's New Horizons principal investigator Alan Stern and the former president of the International Astronomical Union (IAU) Ron Ekers.

It was the IAU that stripped Pluto of its planetary status in 2006. One of the main criteria that denotes a planet was it having "cleared the neighbourhood around its orbit", but as Pluto crosses the orbit of Neptune it did not meet this requirement. This decision was made after a long-winded process of deciding what should define a planet by the IAU, but sadly Pluto did not reach said criteria, argued Ekers.

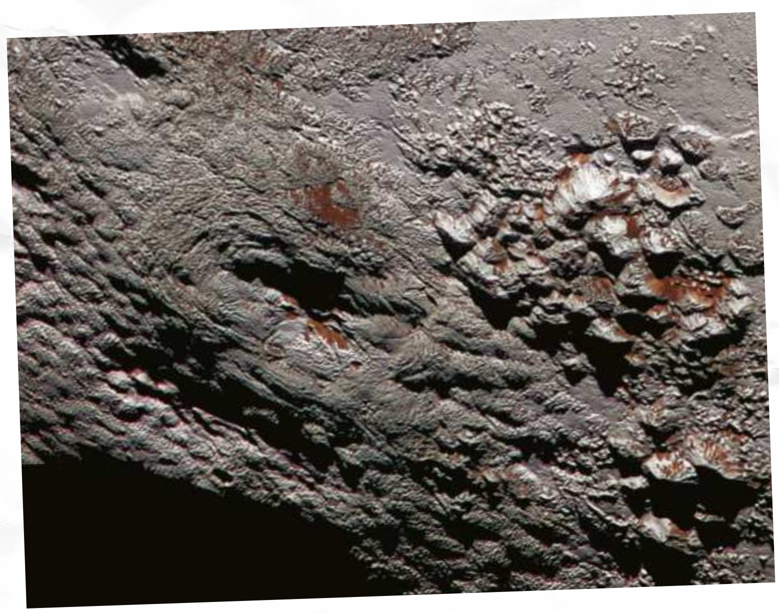
When Stern took to the stage, he argued that Pluto is much more of a world – with oceans, mountains and glaciers just to name some features – and that it is much harder to clear an orbit in the region beyond Neptune than it is closer to the Sun. After the debate a vote was taken; 30 people voted in favour of keeping Pluto as a dwarf planet, whereas a whopping 130 voted in favour of Pluto being a planet.

AMMONIA MAKES PLUTO LOOK YOUNGER

Ammonia – a nitrogen atom with three hydrogen atoms branching off – is a building block of life and a welcome sight to astronomers. As ammonia is a key compound for life as we know it, when it is seen on other planets or other bodies, it ticks an important box when looking for what makes a world habitable. Obviously Pluto has many things going against it in terms of habitability – its tiny size, its huge distance from the Sun, relatively no atmosphere and so on – but ammonia is enough to gain the attention of many astrobiologists.

This compound, however, is short-lived on such an exposed body. In the words of Cristina Dalle Ore, a planetary scientist at NASA's Ames Research Center in Moffett Field, California, United States, ammonia "is a fragile molecule and gets destroyed by ultraviolet irradiation as well as cosmic rays. Therefore, when found on a surface it implies that it had been emplaced there relatively recently, some million years before."

Therefore there must be some form of geological activity depositing ammonia onto the surface. Whether there is recent volcanic activity, active vents or whatever gateway there may be between the surface and the potential subsurface ocean, astronomers are now determined to find out how ammonia is getting to the surface to make Pluto look younger.



EXPLORING THE PAST AND FUTURE OF PLUTO

Due to the enormous distance to Pluto, exploration has been minimal. For a long time any observations relied on Earth-based telescopes, particularly Hubble, which produced the highest resolution maps of the dwarf planet in 2002 to 2003.

NASA, however, deemed this not quite good enough, choosing to send a space probe to Pluto and see what it was all about. New Horizons was the project chosen to do so and was launched on 19 January 2006, beginning its nine-year journey to Pluto. When it arrived in July of 2015, New Horizons flew as close as 12,500 kilometres (7,800 miles) to the planet and revealed an incredibly interesting surface. Upon closer inspection of the data the New Horizons team found potential evidence of a subsurface ocean, not just water-ice frozen under the face of the dwarf planet. This could have amazing repercussions in understanding how water exists in the Solar System.

After the New Horizons flyby, planetary scientists have become more interested in Pluto and are desperate to learn as much about it as possible. This has laid down another challenge at NASA's feet which could soon be picked up by the aerospace engineering company Global Aerospace Corporation (GAC), who are interested in creating the 'Pluto Hopper'.

The idea behind this hopper is to drop a lander onto the surface of Pluto using an inflatable balloon to slow down the craft. One issue with this, however, is that Pluto has an incredibly thin atmosphere. It also has a low surface gravity – only six per cent of Earth's – and the spacecraft would have to slow down a lot as it arrives at high speeds. Although these are hard obstacles to overcome when trying to place a lander on the surface of the tiny dwarf planet, they are doable, and scientists and engineers are continuing to work out how to get back to Pluto one day.

The 'Pluto Hopper' is still in the designing phase of its mission

© Adrian Mann;

NEW HORIZONS AND PLUTO: A BRIEF ENCOUNTER

Date: 19 January 2006
Activity: New Horizons was launched on top of an Atlas V rocket from Cape Canaveral Air Force Station, Florida.

Date: 28 February 2007
Activity: Had a 'gravity assist' from Jupiter to gather more speed, which reduced its journey time by three years.

Date: 28 June 2007
Activity: New Horizons went into hibernation for the long journey.

Date: 6 December 2014
Activity: Engineers woke New Horizons up ahead of its flyby to test equipment.

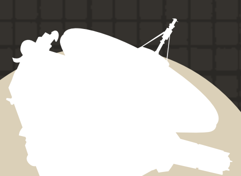
Date: 15 May 2015
Activity: New Horizons had officially imaged Pluto in a better resolution than Hubble.

Date: 14 July 2015
Activity: The day of the flyby had arrived; a historic moment that returned unbelievable data about the dwarf planet.

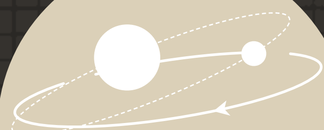
PLUTO'S FACTS AND STATS

153

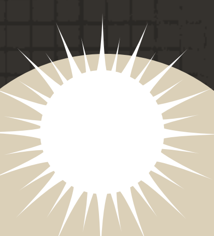
One day on Pluto takes 153 hours. It has a retrograde rotation, meaning it spins from east to west.



NASA's New Horizons was the fastest man-made object launched from Earth at 16.26 kilometres (10.10 miles) per second.



Charon, Pluto's largest moon, also takes 153 hours to complete one orbit around Pluto, meaning this moon never rises or sets.

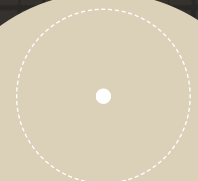


It takes 5.5 hours for sunlight to reach Pluto, as light has to travel 40-times as far than it does to Earth.

1/900

The Sun would be 1/900 the brightness on Pluto than it is on Earth, equal to 300-times the brightness of a full Moon.

Pluto's mountains can reach as high as two to three kilometres (6,500 to 9,800 feet) and are essentially composed of water ice.



There is no evidence to suggest Pluto has a magnetosphere, but its small size and slow rotation suggests it is unlikely.

MOON PROFILE CHARON

The secrets of Pluto's largest moon

Nobody knew it was there until 1978. For almost 50 years after Pluto's discovery in 1930, the dwarf planet had no known companions out there on the edge of the Solar System. Today, of course, in the wake of the New Horizons mission and a myriad of discoveries since the first inklings of the Kuiper Belt came in 1992, we know it positively teems out there. Charon is one of a system of five moons, and Pluto is the largest member of a huge collection of objects orbiting beyond Neptune. The ongoing hunt for a large planet in the extreme reaches of the Solar System has so far come to nothing, and this is the domain of the small, with Pluto's reclassification as a dwarf planet just the first in a whole raft of triumphantly tiny accolades.

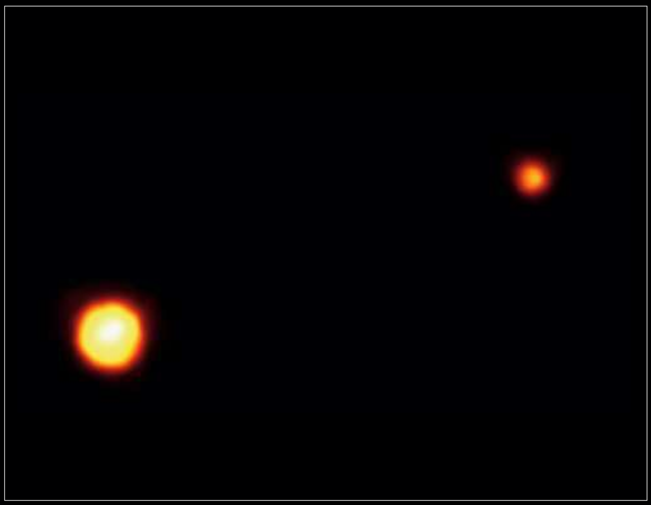
Pluto's largest moon, however, has some remarkable features of its own, despite only having a diameter of 1,212 kilometres (753 miles) – about 10.5 per cent that of Earth's. One-eighth the mass of its co-orbitee Pluto, and half the diameter, it's tidally locked to the larger body, but large enough that the two orbit a centre of mass between them. The International Astronomical Union's general assembly considered a proposal in 2006 to reclassify the pair as a double planet, but despite it being spherical, it wasn't clear Charon was in hydrostatic equilibrium, a state in which the force of gravity is balanced by outward pressure from the body. This state is necessary to give it dwarf planet status.

Charon's name, which it shares with the ferryman who takes souls over the River Styx to Hades in Greek mythology – pronounced with a hard 'K' sound at the beginning – where they're guarded by the three-headed dog Cerberus, comes from its discoverer James Christy, whose wife is named Charlene – he pronounces Charon with a 'sh' sound, as does the New Horizons team. But a 1940 novel by Edmond Hamilton, *Calling Captain Future*, names three Plutonian moons as Charon, Styx and Cerberus. Whatever the origin, the name was officially announced in January 1986, replacing the temporary designation S/1978 P 1. As more moons were discovered around Pluto, they were named Styx; Nix, the Greek goddess of the night; Kerberos – Cerberus was already taken by an asteroid – and Hydra, a nine-headed water monster.

Charon orbits so close to Pluto that when examining photographic plates of the erstwhile planet, taken using the 1.55-metre (61-inch) telescope at United States Naval Observatory Flagstaff Station, all he saw was a bulge in the shape of the tiny disc. By revolving around the disc with time, it revealed itself to be a moon. It wasn't until the development of adaptive optics for Earth-based telescopes that it became possible to resolve the pair as separate discs. The bodies whip around each other once every 6.4 days at an average distance of 19,640 kilometres (12,203 miles), and take 248 years to complete a trip around the Sun.

We had to wait until the New Horizons probe entered the system in 2015 to get a really good look at Charon. A largely grey world of rock and water ice with a reddish cap at its north pole, it remains a fascinating part of the Solar System with more secrets to be discovered.

Below: Charon is half the size of its parent body, dwarf planet Pluto



MOON COMPOSITION

55%
ROCK

45%
ICE

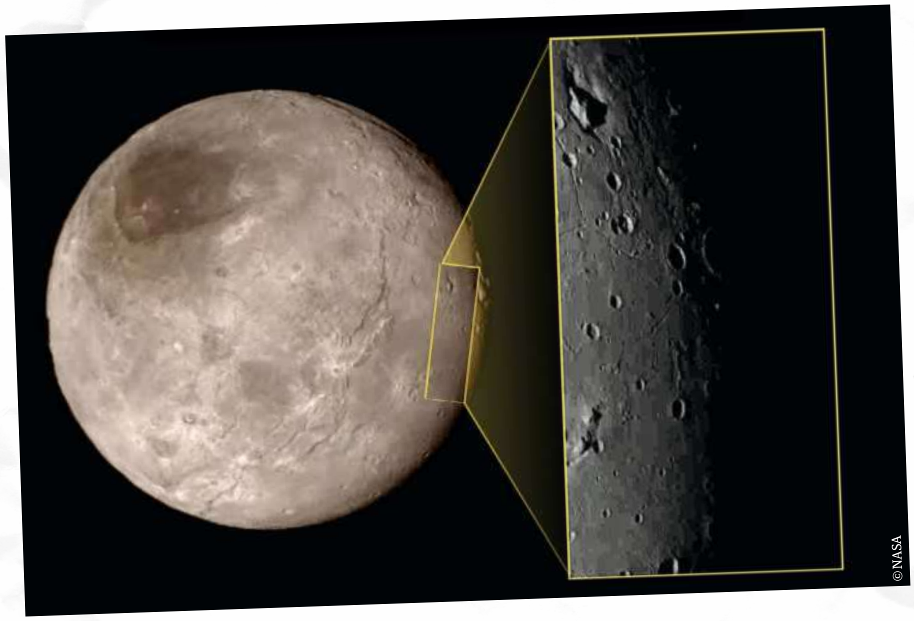
"A FASCINATING PART OF THE SOLAR SYSTEM WITH MORE SECRETS TO BE DISCOVERED"

© NASA

NEWS FROM CHARON

FANTASY FEATURES

Various features on the surface of Charon, imaged by the New Horizons probe, have been given official names by the International Astronomical Union Working Group for Planetary System Nomenclature. The names reflect travellers and explorers, especially those with mysterious destinations. Dorothy Crater, for example, is named after the protagonist from *The Wizard of Oz*, while Caleuche Chasma is named for the mythological ghost ship that travels the seas around the small island of Chiloé off the coast of Chile. Mandjet Chasma is named for one of the boats in Egyptian mythology that carried the Sun god Ra across the sky each day, and Nemo Crater honours the captain of the Nautilus, the submarine in Jules Verne's novels *Twenty Thousand Leagues Under the Sea* and *The Mysterious Island*. The New Horizons team had their own names for distinctive areas of the moon, including Oz Terra, Charon's only highland region, named after the land of Oz, and McCaffrey Dorsum, the moon's only ridge, named after science-fiction author Anne McCaffrey.



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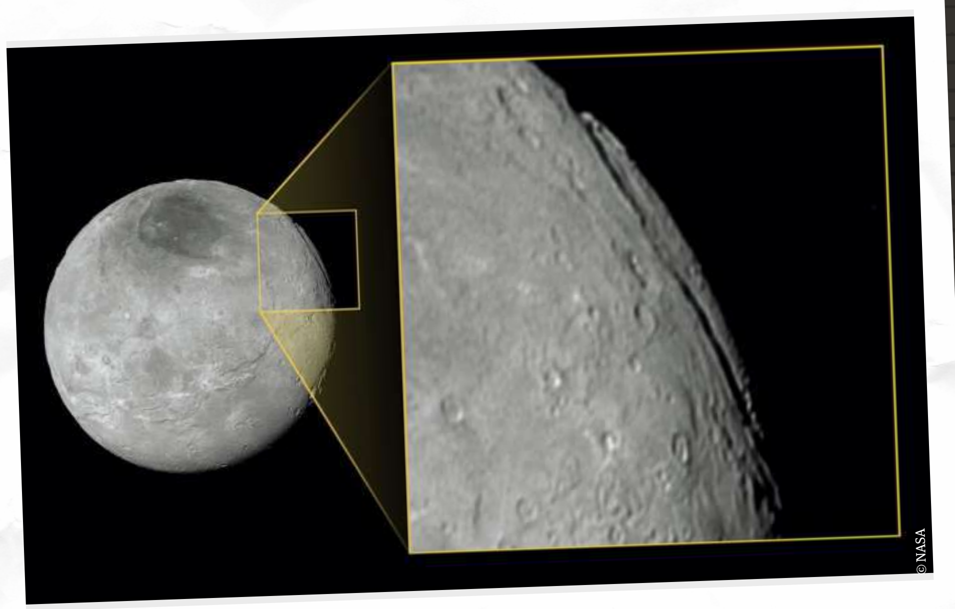
WHAT'S IN THE CAP?

Charon's north polar cap is a different colour to the rest of its surface, and there might be a fascinating explanation: Pluto may be sharing its atmosphere with its largest moon. A study from the Lowell Observatory in Arizona modelled conditions on Charon over the past few billion years and discovered that radiation had been stripping the hydrogen from frozen methane on the dwarf planet's surface. This left behind carbon, which joined with other molecules to make heavier materials more able to stick to the surface rather than be lost to space. These became organic molecules called tholins, which produce the red hue. There was speculation after New Horizons revealed Charon's red pole that the cap was enriched with tholins, which could have gotten there via atmosphere transfer. Pluto's gravity isn't high enough to hold onto its thin atmosphere, but Charon's is powerful enough to capture some of the lost gases. Charon's poles freeze the methane, but it evaporates in summer, leaving the heavier, redder molecules behind.

MAPS MADE

The New Horizons spacecraft did more than take photographs when it passed through the system in 2015. The wealth of data it sent back is still being analysed, years after the probe moved on to targets deeper in the Kuiper Belt. New Horizons only directly imaged 45 percent of the surface of Charon in daylight, meaning there are still secrets left to uncover for future missions, but by stitching together images from a pair of New Horizons' cameras, a team from the Universities Space Research Association's Lunar and Planetary Institute in Texas was able to create a height map of the surveyed areas. From this, the size of surface features could be calculated, including the six-kilometre (3.7-mile) high Tenzing Montes, the moon's highest mountains. This height also allows an insight into their composition – methane ice isn't strong enough to support peaks of that height, meaning they must be made of water ice, frozen harder than rock in the chilling temperatures of -250 degrees Celsius (-418 degrees Fahrenheit).



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FUTURE EXPLORATION OF CHARON

New Horizons passed through the Pluto system without stopping, and is continuing to speed through the Kuiper Belt on its way out of the Solar System as one of the fastest human-made objects ever launched. Another probe could hypothetically spend much more time investigating Pluto and its moons, using Charon as a source of momentum.

The mission – which is purely theoretical at this point, having been demonstrated by New Horizons' software lead Tiffany Finley – could explore each of the moons in the Pluto system, passing each at least five times, returning to Charon after each one for a course-correcting gravity assist. Using an electric propulsion system similar to that on the Dawn mission to Vesta and Ceres, the tour would only use fuel for 'clean-up manoeuvres' designed to make sure it was going in exactly the right direction, making it an efficient way to visit the moons. The Cassini probe did something similar using Titan while touring the moons of Saturn.

The mission could even be extended so that with one final gravity assist the probe would enter the Kuiper Belt and enter orbit around a second dwarf planet. New Horizons' visit to Pluto was a big success, but it was necessarily limited by the speed at which it passed the system. A second probe spending more time there would perhaps be able to answer many of the remaining questions about Pluto, Charon and its scattering of small moons.

Below: Artist's impression of the New Horizons probe flying by Pluto and Charon

CHARON BY NUMBERS

19,640 KILOMETRES
The average distance between Charon and Pluto

40 KILOMETRES
Diameter of Kubrick Mons, a strange mountain in a moat on Charon

7.5 BILLION KILOMETRES
The distance from Earth to Pluto when they're on opposite sides of the Sun

-258°C
Winter temperature in Charon's north polar region

-213°C
Summer temperature in Charon's north polar region

14 KILOMETRES
The depth of Charon's Caleuche Chasma, roughly seven-times deeper than the Grand Canyon

SIX KILOMETRES
Height of Tenzing Montes, Charon's highest peaks

THE EVOLUTION OF CHARON

Date: 4.5 billion years ago
Activity: Two Kuiper Belt objects collide and go into orbit around a shared barycentre.

Date: 1930
Activity: Discovery of Pluto by Clyde Tombaugh.

Date: 1978
Activity: Discovery of Charon by James Christy.

Date: 1980s
Activity: Pluto and Charon eclipse one another several times, allowing astronomers to study their spectra and work out their surface composition.

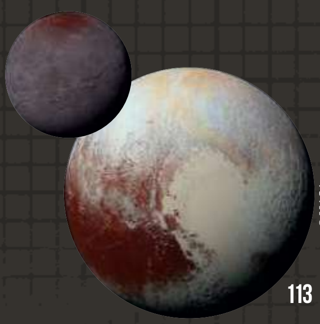
Date: 1994
Activity: Hubble images Pluto and Charon from 4.4 billion kilometres (2.7 billion miles) away.

Date: 2007
Activity: Observations by the Gemini Observatory suggest there are active cryogeysers on Charon's surface.

Date: 2015
Activity: New Horizons arrives in the system, gathers data and then leaves.

Date: 2017
Activity: NASA's Ames Research Center confirms Charon once had active plate tectonics like Earth.

Date: 2019
Activity: A geomorphological map of Charon's surface is published, dividing the surface into 16 types.



IS THERE A PLANET NINE?

Mike Brown is the man who killed Pluto, but have the tables turned to leave his own theory of a ninth world in doubt?

Reported by David Crookes

Mike Brown is a professor of planetary astronomy at the California Institute of Technology (Caltech), but he is also known as the 'Pluto killer'. It was 2006 when the International Astronomical Union downgraded Pluto's planetary status to that of a dwarf. Brown led the charge following his discovery of Eris in January the previous year, and it meant the Solar System was back to having just eight planets. For some, the move was unthinkable. Dr Alan Stern, who headed up the New Horizons mission that sent a spacecraft to Pluto, was particularly angry. Yet it had been coming since 1992, when a new object was discovered in what became known as the Kuiper Belt beyond the orbit of Neptune.

What few saw coming, however, was the emergence of a new candidate for the ninth planet. As if to rub salt in the wounds of those who felt Pluto's status should be reinstated, it was Brown – along with a fellow professor of planetary science at Caltech, Konstantin Batygin – who put the theory forward ten years later based on observations of six extreme trans-Neptunian objects, or ETNOs.

One of them, Sedna, is 40 per cent the size of Pluto, and it behaves in an odd way. Rather than forming an elliptical ring around the Sun as expected, this large planetoid in the outer reaches of the Solar System – some three-times farther away than Neptune – has an exceptionally long and elongated orbit. Taking about 11,400 years to complete its orbit, it will at some point be 76 astronomical units (AU) from the centre of our Solar System – that's 76 times the distance between Earth and the Sun – but it will swing out to more than 900 AU.

What's more, it's not alone. Brown and Batygin observed a cluster of six other ETNOs with similar orbits, and they tilt on their axis in the same direction. They don't appear to be as affected by the known giant planets in our Solar System as other trans-Neptunian objects, so the two scientists came up with an explanation.

According to Brown and Batygin's calculations and modelling, the unexpected clustering of objects is due to the gravitational pull of an as-yet-undiscovered ninth planet that is between 13 and 26 times farther out than Neptune. This hypothetical celestial body would have a predicted mass between five and ten times that of Earth. Its orbit would be elongated, ranging between 400 and 800 AU.

It's an exciting proposition, yet one that has not gone unchallenged. A study led by Kevin Napier at the University of Michigan has cast doubt on the theory. By observing 14 far-off rocky bodies discovered by three surveys – five each from the Dark Energy Survey and the Outer Solar System Origins Survey and a further four picked up by astronomers Scott Sheppard, Chad Trujillo and David Tholen – they say there is no

"IT WOULD HAVE BEEN MORE EXCITING IF OUR FINDINGS SHOWED STRONG EVIDENCE FOR CLUSTERING, AND THUS FOR PLANET NINE" KEVIN NAPIER

PLANET NINE BY THE NUMBERS

5-10
times the mass of Earth

2-4
times the radius of Earth

400-800
times farther from the Sun than Earth

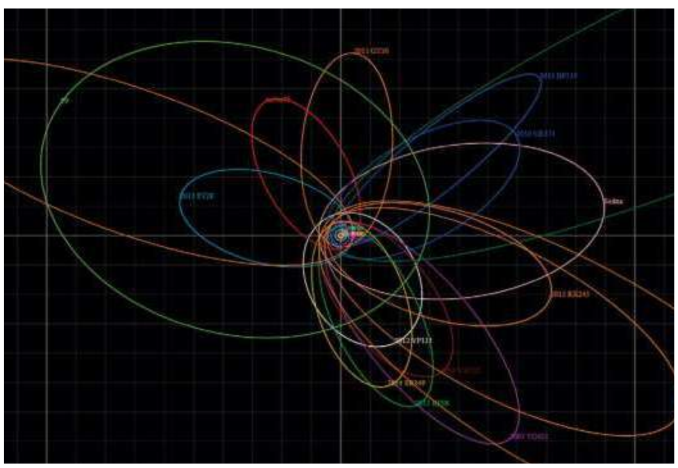
0
Number of observations

6
Number of extreme trans-Neptunian objects which appear affected by Planet Nine

10,000-20,000
Years to make a full orbit of the Sun

20 YEARS
Time Mike Brown estimates it would take for a probe to reach the planet

0.2-0.5
The hypothesised eccentricity of Planet Nine's orbit



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Top: An artist's concept of Planet Nine in orbit far from the Sun

Above: The original six ETNOs used by Brown and Batylin to hypothesise about Planet Nine, along with the planet's theorised orbit (in green) and eight other ETNOs

evidence of ETNO clustering that would firmly indicate the existence of an extra planet.

Instead, they say the findings by Brown and Batygin are due to observational bias. In other words, the new research reckons that Planet Nine's apparent existence is mainly based on the direction in which the two scientists' telescopes looked. Since Brown and Batygin observed just a small section of sky, the selection of ETNOs was limited. This, says Napier, weakens the case.

"Simulations have shown that Planet Nine causes the orientations of the ETNOs' orbits to cluster on timescales comparable to the age of our Solar System," Napier explains to **All About Space**. "There are now on the order of a dozen known ETNOs that appear to exhibit this clustering, and if you look at the data, the clustering appears to be rather robust.

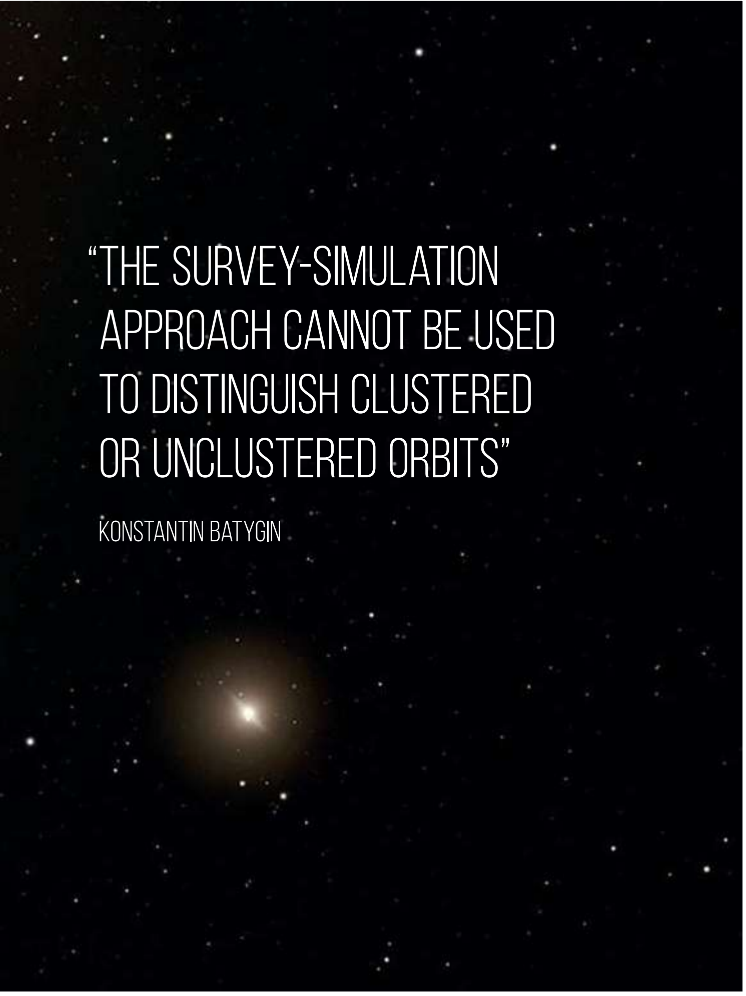
"But you cannot simply look at the data and draw robust conclusions because of this effect called observational bias. It takes into account factors such as where you pointed the telescope, when you took the observation and how faint of an object the telescope was able to see.

"Because the ETNOs are on exceptionally long, skinny orbits, they can only be seen for a very short segment, when they are closest to the Sun. This makes the observational biases present in their discovery rather severe. Until our study, nobody had performed a meta-analysis on all of the ETNOs discovered by surveys with calculable biases. It turns out that when you properly account for these observational biases, the population of ETNOs we observe is fully consistent with a uniform – rather than a clustered – underlying distribution."

In carrying out their research, Napier and his team decided to look at ETNOs that were not studied by Brown and Batygin. Those original six were discovered by surveys with unknown biases, "so we were unable to properly analyse them," explains Napier. "We wanted to test an independent sample because in a larger, better controlled sample, you would expect the significance of the clustering to either stay the same or to increase. We found the significance decreased."

Napier's team did include two of the original six objects after their main analysis, however, giving them a total of 16. "We still found that the observations were consistent with a uniform underlying distribution," he adds. But does that mean talk of a Planet Nine is off the table?

Causing some confusion about the conclusion is the title of Napier's academic paper, entitled: No Evidence for Orbital Clustering in the Extreme Trans-Neptunian Objects. It jars with the content of the work itself, and Batygin has not been slow



“THE SURVEY-SIMULATION APPROACH CANNOT BE USED TO DISTINGUISH CLUSTERED OR UNCLUSTERED ORBITS”

KONSTANTIN BATYGIN

© Caltech

to seize on this. “The Napier et al study does not actually draw the conclusion in the title,” he tells us. “The work demonstrates that the survey-simulation approach cannot be used to distinguish between clustered or unclustered orbits, and this is not particularly surprising. Heavily biased surveys like the Outer Solar System Origins Survey or Dark Energy Survey are very hard to de-bias, and given the limited number of detections in each survey, the fact that survey-simulation cannot rule out any distribution is not perplexing.”

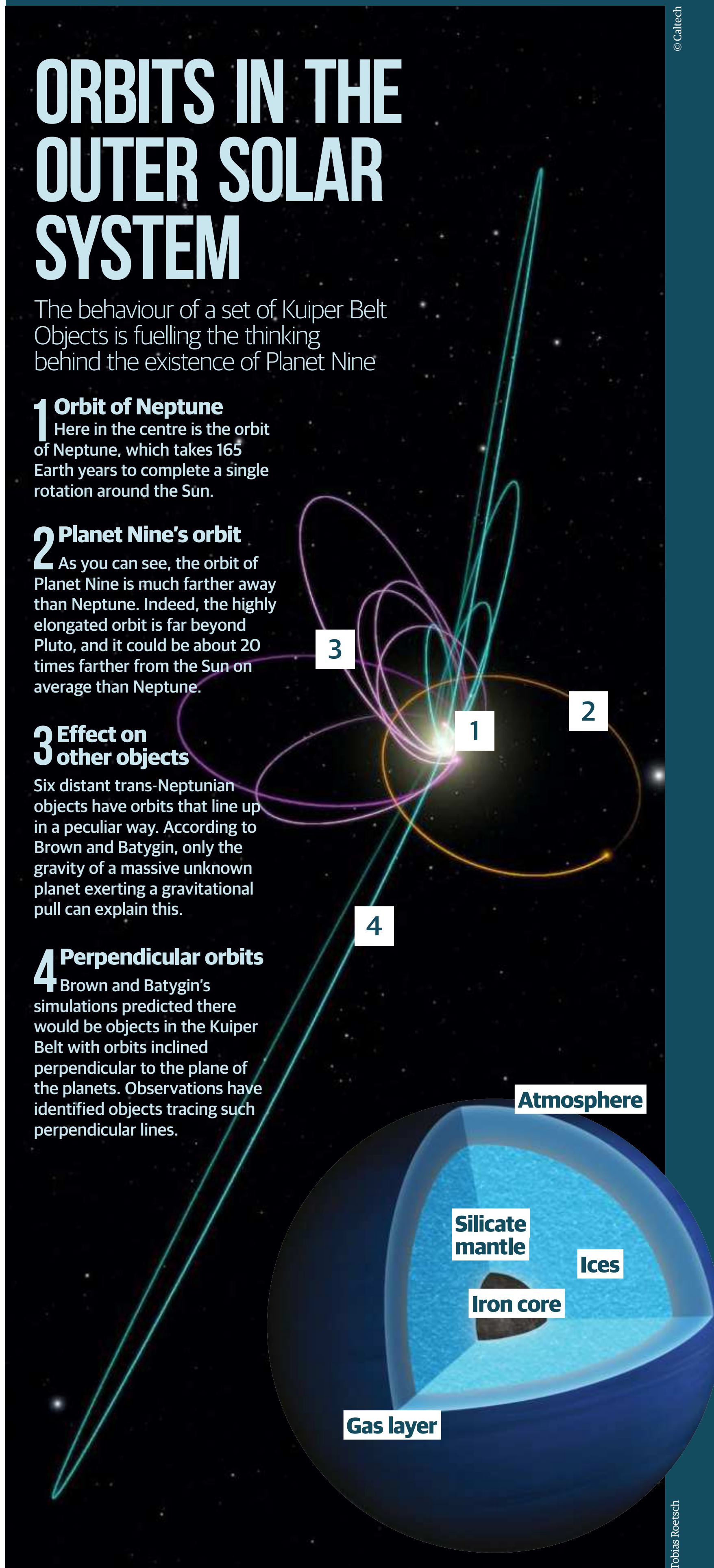
Brown agrees wholeheartedly. “If you read the paper really carefully, then the correct statement from the Napier analysis would be something like: ‘Our survey was very biased, and this could not detect clustering at the level previously detected.’ It’s a big leap that there is no clustering, and it’s one they don’t make in the paper, but do in interviews. In fact, if we add their new objects to our full dataset instead of using their much more limited dataset, the clustering actually improves.”

In our interview, Napier admits that the work doesn’t rule out the existence of Planet Nine, saying only that it has “certainly weakened the case for it”. He says he would have preferred the conclusion to have backed the original hypothesis. “It would have been more exciting if our findings showed strong evidence for clustering in the ETNOs, and thus for Planet Nine,” he says.

“That being said, we still find our results exciting,” he adds. “Even if it turns out that Planet Nine doesn’t exist, there must be some explanation

ORBITS IN THE OUTER SOLAR SYSTEM

The behaviour of a set of Kuiper Belt Objects is fuelling the thinking behind the existence of Planet Nine



1 Orbit of Neptune
Here in the centre is the orbit of Neptune, which takes 165 Earth years to complete a single rotation around the Sun.

2 Planet Nine’s orbit
As you can see, the orbit of Planet Nine is much farther away than Neptune. Indeed, the highly elongated orbit is far beyond Pluto, and it could be about 20 times farther from the Sun on average than Neptune.

3 Effect on other objects
Six distant trans-Neptunian objects have orbits that line up in a peculiar way. According to Brown and Batygin, only the gravity of a massive unknown planet exerting a gravitational pull can explain this.

4 Perpendicular orbits
Brown and Batygin’s simulations predicted there would be objects in the Kuiper Belt with orbits inclined perpendicular to the plane of the planets. Observations have identified objects tracing such perpendicular lines.

© Caltech

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for the orbital behaviour of some of the strangest objects in our Solar System. Examples of such anomalies include Kuiper Belt Objects on highly inclined orbits and objects that never come closer to the Sun than twice the distance of Neptune. Mysteries like this are what keep us going."

As far as Batygin is concerned, the mystery surrounding Planet Nine is still in favour of it being out there somewhere. He says it has been clear for a long time that individual surveys cannot overcome their own biases to rigorously determine clustering one way or another. "In fact, this has already been pointed out multiple times, and the Napier et al analysis combines the well-characterised surveys, but still finds the same answer," he says. "For this reason, in order to determine the 'false-alarm probability' of the clustering, it makes sense to instead do an observability analysis which takes advantage of the full dataset to determine statistical significance." Batygin says he did exactly this in a paper with Brown published in 2019: "The analysis demonstrates that the chances that the data are not clustered is only 0.2 per cent."

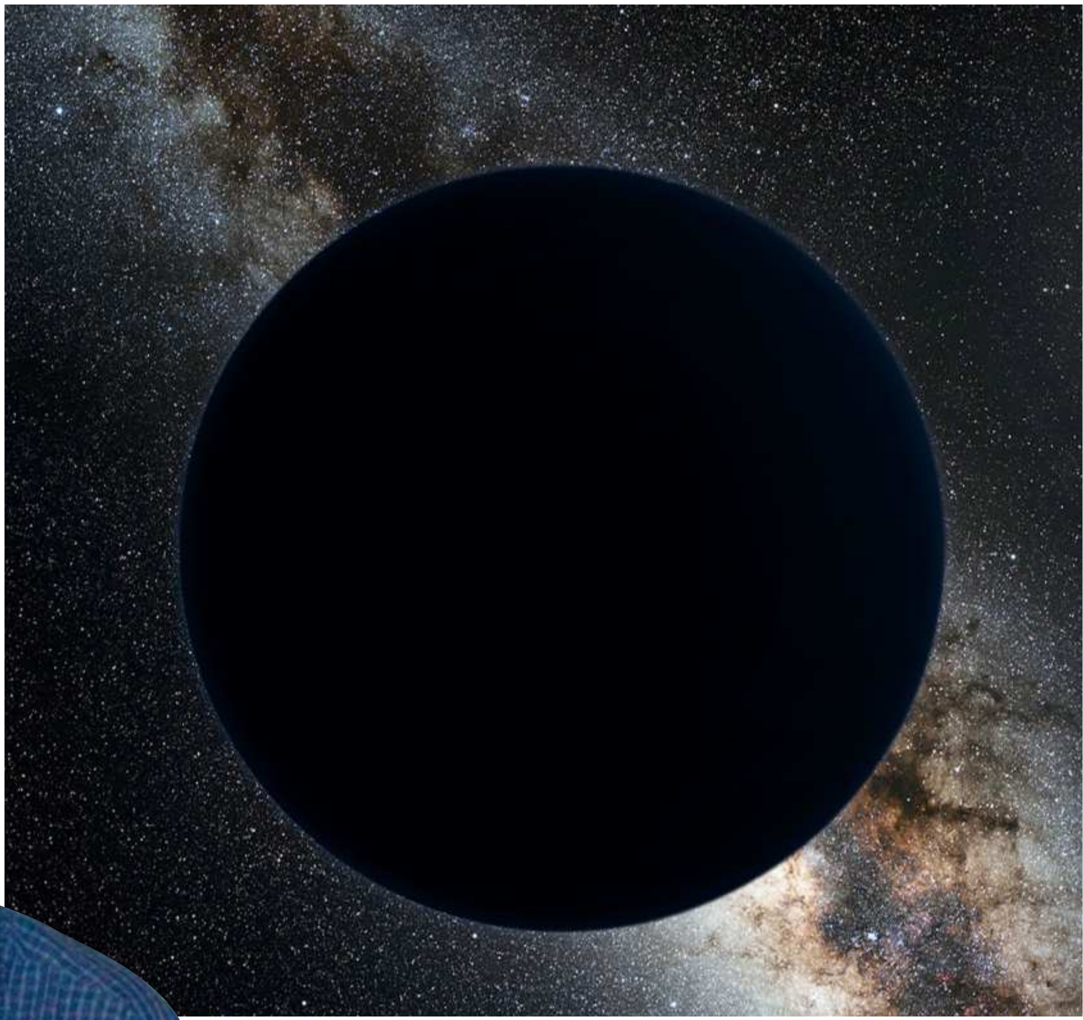
By this, Batygin is theorising that the chance of clustering happening naturally without any gravitational pull from a body such as Planet Nine is extremely slim. What's more, as well as the clustering of orbits, the ETNOs with perihelia beyond 50 AU are too sufficiently distanced from Neptune to experience significant gravitational perturbations from it, so it points to something having an effect.

"An important point to understand is that the Planet Nine hypothesis is not just one thing," Batygin says. "There is a collection of lines of evidence that all paint the same picture: clustering of the apsidal lines, grouping of the angular momentum vectors, detached perihelia of long-period Kuiper Belt Objects, excitation of distant Kuiper Belt Objects to high inclinations and generation of the retrograde centaur population of the outer Solar System. The fact Planet Nine ties all these outer Solar System anomalies together gives me some confidence that we are on the right track."

In that sense, he doesn't perceive the study by Napier to have much of an effect on the original hypothesis. "There is one more very important point to understand, which routinely gets lost in translation," he continues. "The distant Kuiper Belt is made up of stable as well as unstable objects, and

Right: An artist's impression of Planet Nine with the Sun in the very far distance, circled by the orbit of Neptune

Below: Brown bears the nickname of 'Pluto killer'



FURTHERING THE CASE FOR PLANET NINE

American astronomer Mike Brown has worked on the hypothesis of another world for the last five years

Some scientists have been unable to create a computer simulation that accounts for the clustered trans-Neptunian objects which form the basis of the theory of Planet Nine. Does this cast doubt over its existence in your mind?
Many groups have reproduced computer simulations that make the Planet Nine cluster. The physics is well understood. It is neither difficult nor mysterious.

Would you say the suggestion that you observed a small portion of the sky during a specific part of the year at a specific time of day is valid?
I haven't heard that suggestion. Our survey is the only one that doesn't do that. The others are much more limited.

How strong is the evidence for a Planet Nine in light of the recent study?
The Napier paper neither adds nor subtracts to the Planet Nine hypothesis, though adding in the new objects would strengthen the hypothesis if we combined it with our full dataset – we haven't done this thoroughly yet, though. I would say the Planet Nine hypothesis is as strong as it used to be.

in the Planet Nine story, it doesn't matter what the unstable objects do.

"If you look at the data, the stable, high-perihelion objects cluster very well, while the unstable objects are all over the place. That's what the theoretical model predicts too. You can imagine a whole range of observational biases that can cause clustering, but it's impossible to bias based on dynamical stability. Because the Napier et al dataset is roughly half stable, it's not a huge surprise they cannot prove that it's clustered." But does that still mean it has to be a planet causing the clustering? With the theory suggesting that gravity is at play, planets are not the only objects able to exert a gravitational pull. Dark matter or a primordial black hole are among the alternative suggestions.

Napier reckons a planet would be the most likely explanation, so long as it's one day proved that the clustering is persistent. "It's hard to imagine it being caused by a dynamical mechanism other than Planet Nine if the clustering is persistent and not transient," he says. But recent work has shown that it's possible we are observing a temporary clustering of the ETNOs. It's clear more work needs to be done.

Certainly, the hypothesis of a Planet Nine is not going away any time soon. "I'm still quite optimistic that Planet Nine exists," says Batygin, with the use of the word 'quite' being notable. Napier, on the other hand, concludes: "I'm hopeful, but not optimistic. It might be there; it might not." Its existence would make life easier, but only one thing would really nail it. "Direct detection would be best," says Batygin, "and the answer to anything short of that is basically more data."

Napier agrees, and both are pinning their hopes on the Vera C. Rubin Observatory in Chile, which is coming online soon. The Legacy Survey of Space and Time at the observatory means the census of trans-Neptunian objects will expand substantially. One of the reasons why sufficient data has been hard to come by so far is access to telescopes and a focus on ETNOs in particular. Estimates are that the survey will discover more ETNOs, and with that data we'll be able to make a compelling statement.

One thing's for sure, there's a willingness for a discovery. In truth, most scientists would love to actually find Planet Nine. "A new planet would be extremely cool, and it would solve a lot of anomalies that we don't understand about our Solar System," Napier says. "But we have to entertain the possibility that there is no Planet Nine and continue searching for alternate explanations of those anomalies." We can only wait with bated breath.

David Crookes
Science and technology journalist
David has been reporting on space, science and technology for many years, has contributed to many books and is a producer for BBC Radio 5 Live.

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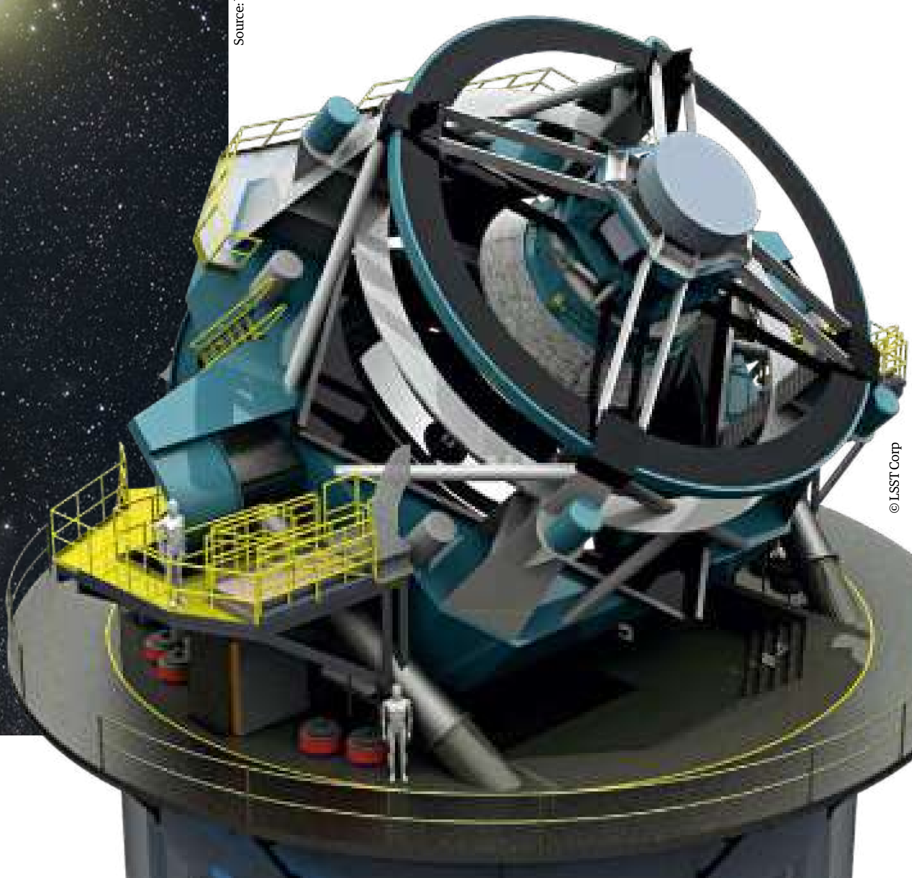

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Left: The Vera C. Rubin Observatory will be able to provide new data on ETNOs

THE THEORIES

What could be affecting the extreme trans-Neptunian objects?

1 Planet Nine

Modelling in 2016 by Brown and Batygin at Caltech hypothesised that six ETNOs had similar orbits because a large planet well beyond Neptune was exerting a massive gravitational pull on them. The scientists are sticking to this theory, and 19 ETNOs are now shown to exhibit a similar tilt and eccentric orbital pattern. This theory has yet to be proved or disproved.

© Getty

2 There's no clustering

According to a recent study headed by Napier, it is possible that there is no clustering in the first place. Other work suggests that any clustering could be temporary, and if either of these are the case then the likelihood of any gravitational pull being exerted is ruled out, thereby leaving any case for a Planet Nine severely dented.

© NASA

3 Something else is at play

If the ETNOs are indeed being affected by something in the Solar System, does it have to be a planet? Some scientists are looking into the possibility of a primordial black hole – a black hole which formed soon after the Big Bang – but these are still hypothetical. Dark matter is another potential theory, but again it's one hypothetical explaining another.

© NASA

'FARFAROUT' OFFICIALLY THE SOLAR SYSTEM'S MOST DISTANT OBJECT

This recently discovered trans-Neptunian object lies some 140 astronomical units from the Sun

The planetoid dubbed 'Farfarout' was first detected in 2018 at an estimated distance of 140 astronomical units (AU) from the Sun – farther away than any object had ever been observed. One AU is the average Earth-Sun distance – about 93 million miles, or 150 million kilometres. For perspective, Pluto orbits at an average distance of about 39 AU.

Farfarout's inherent brightness suggests a world roughly 400 kilometres (250 miles) wide, barely enough to qualify for dwarf planet status. But the size estimate assumes the world is largely made of ice, and that assumption could change with more observations.

Speaking of more observations, the detection team has now collected enough additional data to confirm the existence of Farfarout and nail down its orbit. As a result, the planetoid just received an official designation from the Minor Planet Center in Cambridge, Massachusetts, which identifies, designates and computes orbits for small objects in the Solar System.

That new designation, announced on 10 February in a Minor Planet Center electronic circular, is 2018 AG37. Farfarout will also receive a catchier official moniker down the road. "A single orbit of Farfarout around the Sun takes a millennium," discovery team member David Tholen, an astronomer at the University of Hawaii, said. "Because of this long orbital period, it moves very slowly across the sky, requiring several years of observations to precisely determine its trajectory."

Astronomers spotted Farfarout using the Subaru Telescope on Mauna Kea in Hawaii and traced its orbit using the Gemini North and Magellan telescopes. "Only with the advancements in the last few years of large digital cameras on very large telescopes has it been possible to efficiently discover very distant objects like Farfarout," co-discoverer Scott Sheppard, a Solar System small bodies scientist at the Carnegie Institution for Science, said.

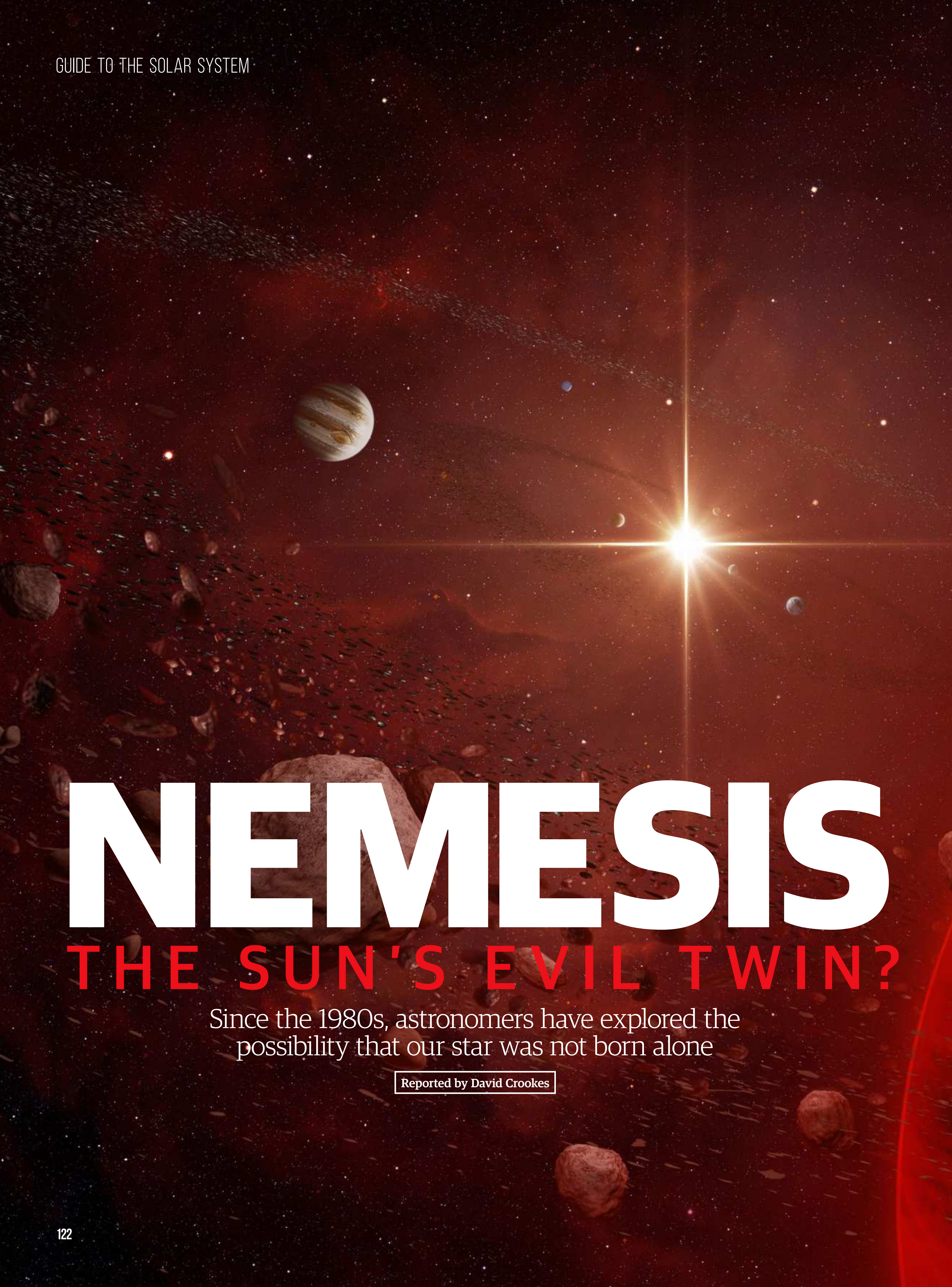
Farfarout is currently about 132 AU from the Sun, the researchers determined. And its orbit is now known to be very elliptical, swinging between extremes of 27 and 175 AU, thanks to gravitational sculpting by Neptune. "Farfarout was likely thrown into the outer Solar System by getting too close to Neptune in the distant past. Farfarout will likely interact with Neptune again in the future, since their orbits still intersect," Chad Trujillo, an exoplanet astronomer at Northern Arizona University from the National Science Foundation's NOIRLab, said.

Because Neptune plays such a large role in Farfarout's life, the planetoid likely cannot help astronomers in the hunt for Planet Nine, the big hypothetical world that some astronomers think lurks unseen in the far outer Solar System. Planet Nine's existence has been inferred from its putative gravitational influence on small bodies very far from the Sun, whose orbits cluster in odd and interesting ways. But the small worlds that astronomers look to as breadcrumbs in the Planet Nine search are free of Neptune's influence, unlike Farfarout.

> "FARFAROUT WAS LIKELY THROWN INTO THE OUTER SOLAR SYSTEM BY GETTING TOO CLOSE TO NEPTUNE IN THE DISTANT PAST"
>
> CHAD TRUJILLO

The team that spotted Farfarout is well known for peering deep into the dark and frigid outer Solar System. In 2018 the researchers also found distant object Farout and a faraway dwarf planet nicknamed 'the Goblin'. Farfarout's distance record refers to its current location. There are a number of other objects, such as the dwarf planet Sedna, whose orbits take them much farther away from the Sun than Farfarout's maximum orbit. And scientists think there are trillions of comets in our Solar System's Oort Cloud, which begins about 5,000 AU from the Sun.

Right: The small, far-flung world is thought to be comprised of ice and rock, like a comet



NEMESIS
THE SUN'S EVIL TWIN?

Since the 1980s, astronomers have explored the possibility that our star was not born alone

Reported by David Crookes

What do you get if you cross the dinosaurs with millions of comets and an evil twin of our Sun that has not only wreaked havoc on Earth multiple times but has long been hidden from view? Anxious? Fearful? Maybe both? For while it may sound like a terrible joke. The intriguing punchline once caused some alarm – and raised a mystery that had astronomers hooked for quite some time.

Welcome to Nemesis, the Sun's hypothetical long-lost companion which has been speculated to be circling in the edges of the Solar System. Proposed by Richard A. Muller, an American physicist and professor of physics at the University of California, Berkeley, it gained some ground in the 1980s with the suggestion that it was behind a series of mass extinction events here on Earth.

The theory grew from a 1983 study by two palaeontologists, David Raup and Jack Sepkoski. They had analysed the extinction rates of 27,000 marine animals which perished during the past 250 million years and pointed towards five mass wipeouts since the Late Permian era, in which more than 75 per cent of species disappeared. They went on to suggest that these catastrophic extinction events were uniformly spaced, taking place every 26 million years, but scientists could not quite fathom why.

Various studies emerged looking at phenomena on Earth, but the belief that a large asteroid wiped out the dinosaurs – a hypothesis by Luis and Walter Alvarez in 1980 – suggested extraterrestrial forces could be at play. It was on this basis that Muller came up with the idea that the comet which smashed into Earth 66 million years ago had been among a humongous group of bodies disrupted by a theoretical red dwarf star. He said it affected the orbits of these objects and sent them

Illustration © Tobias Roetsch

hurtling towards our Sun, smashing into whatever they encountered.

That in itself would have been rather eye-catching, but here is where things became even more interesting. Muller's theory postulated that this star was the Sun's undetected companion – the 'evil twin' that we alluded to at the start. He also reckoned the reason why there may have been this notable cycle of mass extinction events was because the red dwarf star was regularly putting itself among the set of icy rocks that make up the equally theoretical Oort Cloud in the outermost reaches of the Solar System.

It would do so every 26 million years, he says, neatly accounting for the calculated apocalyptic timeframe on Earth. But in order to do this the red dwarf star needed to be in a 1.5 light year elliptical orbit, periodically bringing it closer to the Oort Cloud and sending comets hurtling our way. What's more, the theory continued, there was enough of a gravitational pull on the 'death star' by the Sun to prevent it from drifting away.

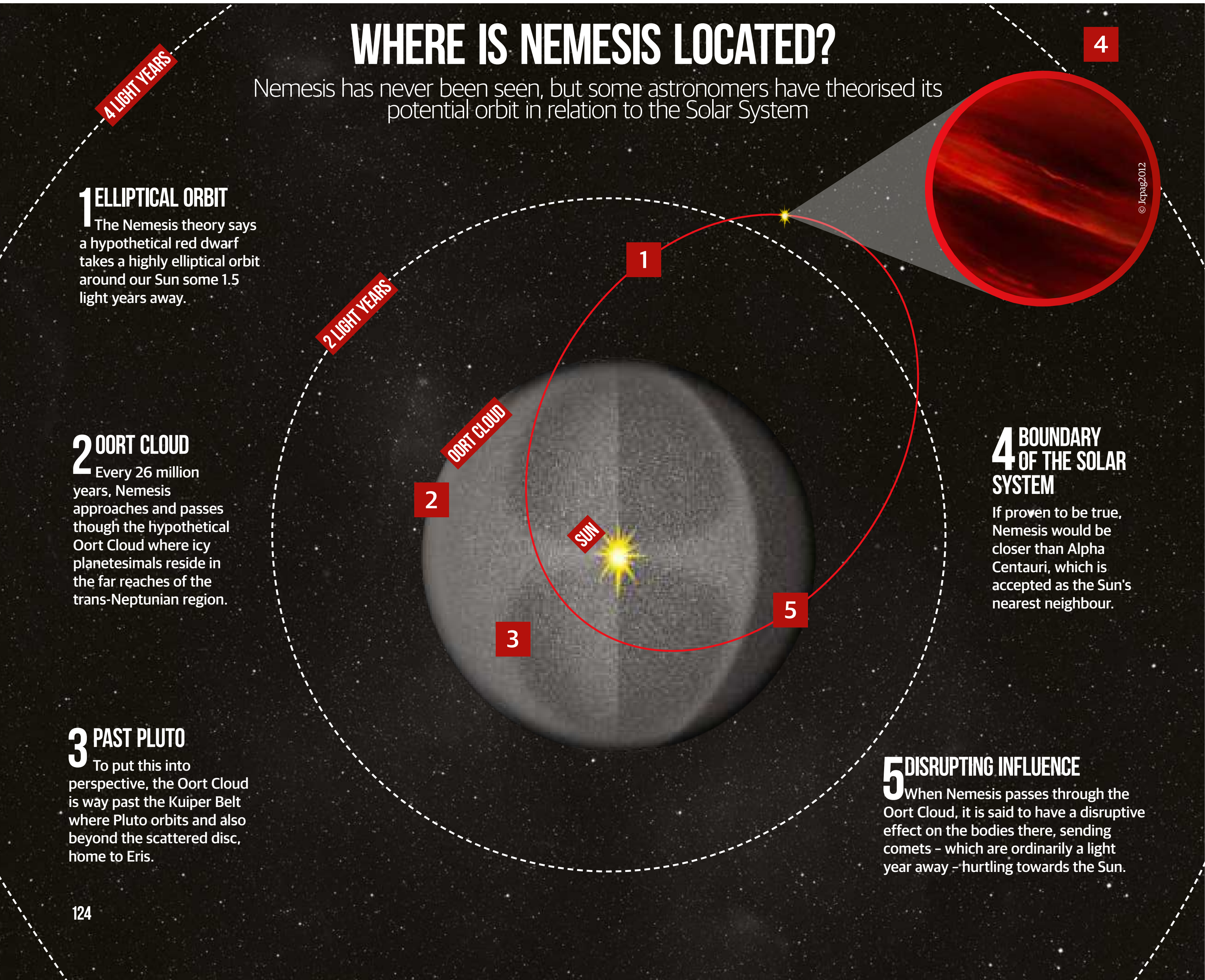
When Muller presented his hypothesis in 1984, it caused international controversy. The scientist was suggesting that the companion star was born at the same time as the Sun, and so was part of a binary star system – that is, one gravitationally bound and orbiting a common centre of mass. Yet in the last 35 years there has never been any sighting, even though it's not been for a lack of trying.

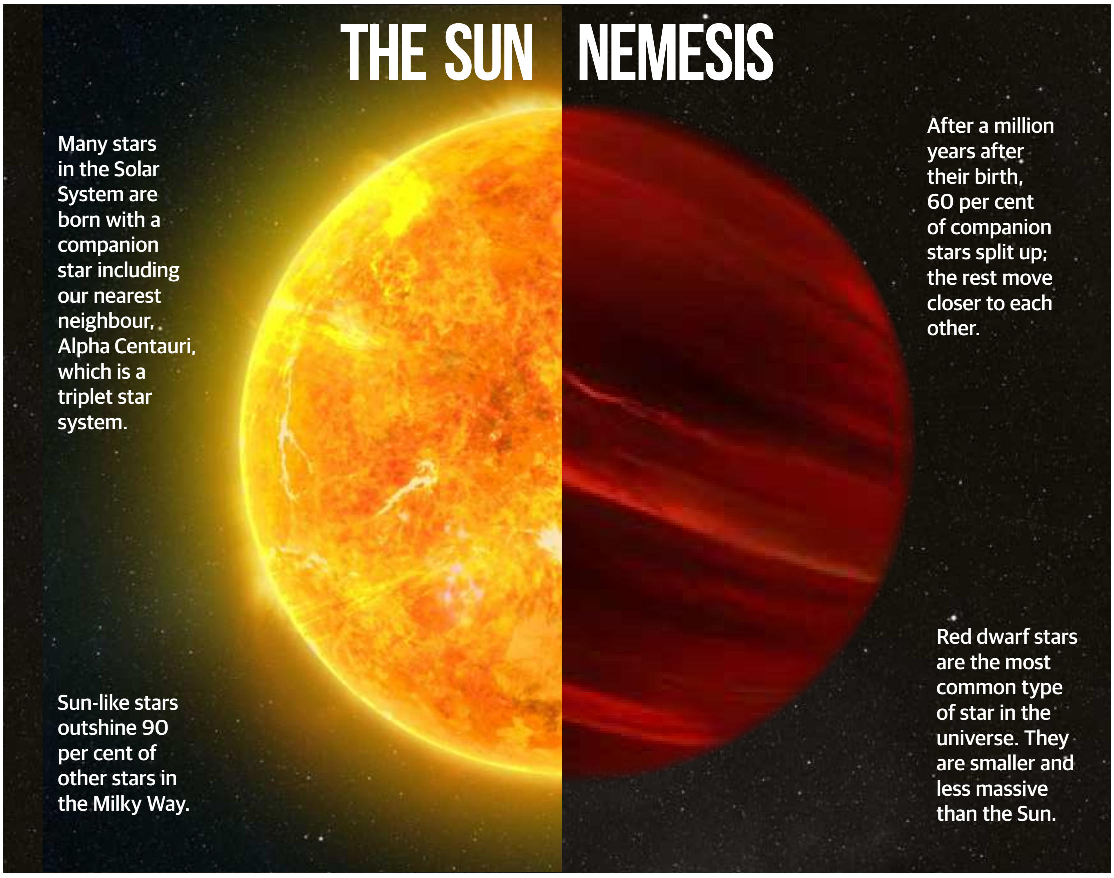
In many ways this is rather odd. Muller said Nemesis was likely to have a magnitude between seven and 12 and that it should be possible to view it through a small or medium telescope. But the Infrared Astronomical Satellite – the first space telescope to perform a survey of the night sky at infrared wavelengths – did not see any signs of it during the 1980s, while the Two Micron All-Sky Survey, or 2MASS, which surveyed the sky between 1997 and 2001, couldn't detect an additional star in the Solar System either.

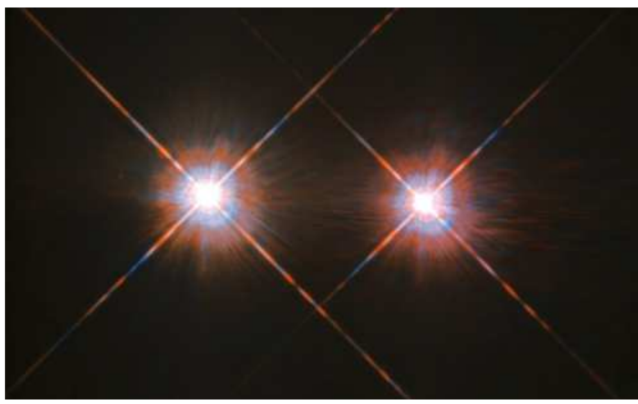
The best shot was thought to be NASA's Wide-field Infrared Survey Explorer (WISE), which spotted a brown dwarf 7.2 light years away in 2014. But it wasn't Nemesis. In actual fact, when Kevin Luhman, an astronomer at Pennsylvania State University's Center for Exoplanets and Habitable Worlds, analysed images from WISE a year earlier in the outer Solar System, there was simply no sign of the companion star that Muller had proposed.

Instead, evidence kept stacking up against it. For starters, some astronomers questioned the inherent

> "STARS GENERALLY DO NOT FORM IN ISOLATION BUT ARE BORN TOGETHER IN GROUPS WITHIN CLOUDS OF GAS AND DUST OR NEBULAE" PAVEL KROUPA







stability of Nemesis' proposed orbit. They said the star would come within the gravitational pull of other stars moving through the galaxy. Others cast doubt that extinction events follow a set cycle. "There is a tendency for people to find patterns in nature that do not exist," said Coryn Bailer-Jones from the Max Planck Institute for Astronomy in 2011. "Unfortunately, in certain situations traditional statistics plays to that particular weakness."

Bailer-Jones said the impact rate of asteroids and comets had been judged to be steadily increasing over the past 250 million years on the basis of the number of craters of different ages. But he argued that periodic variations could be ruled out: "From the crater record, there is no evidence for Nemesis," he concluded. "What remains is the intriguing question of whether or not impacts have become ever more frequent over the past 250 million years."

On that basis it is surely a matter of 'case closed'. Here we have an intriguing idea that many of us would wish to be true, and yet in reality it sounds merely fantastical, with evidence that is flaky at best.

But that isn't telling the full story, and there has been a little matter of a dwarf planet called Sedna to consider, which some astronomers reckoned was additional proof of a twin for the Sun. It is, at 8 billion miles away, one of the most distant bodies in the Solar System, and it pursues an extremely elongated orbit. Discovered in 2003 by a team led by Mike Brown, an astronomer at the California Institute of Technology, it has certainly caught the imagination, but what does it really prove?

Well, there has been a theory that Sedna's wonky orbit could only be the result of a large and distant binary companion to the Sun pulling it out to such a distance. What else, scientists argue, could take the dwarf some 200-times further from the Sun than Neptune every 11,400 years? A study in 2015 seemed to lend credence to this argument

Above left: An infrared sky survey by WISE failed to discover evidence of Nemesis

Above right: Binary star systems are not uncommon - the closest to us is Alpha Centauri A and B, along with faint red dwarf C

THE THEORIES

Is there really something big and influential somewhere out there causing mass extinctions?

THE NEMESIS THEORY

Richard A. Muller's theory suggests the Sun has a companion red dwarf star named Nemesis which has an unusual orbit and causes mass extinctions on Earth every 26 million years or so by having a chaotic impact on bodies in the Oort Cloud.

OUR DANGEROUS SUN

In 2008, a computer simulation by researchers at Cardiff University suggested our Solar System bounces up and down through the plane of the galaxy. Gravitational forces may dislodge comets from the Oort Cloud and send them cascading inwards.

A BROWN DWARF

Nemesis may not be a red dwarf, but a brown one. If that was the case then it would go some way towards explaining why astronomers have struggled to see it: brown dwarfs have a low intrinsic brightness, making them harder to discover.

OTHER PLANETS

There is an acceptance that there are other planets in the outer region of the Solar System. These have never been found, although computer simulations continue to rule in the possibility that they are out there exerting a gravitational influence.

GAS GIANT TYCHE

Scientific analyses suggest extinctions on Earth don't happen at regular, repeating intervals. Some astrophysicists propose a less disruptive gas giant in the Oort Cloud instead, dubbed Tyche – a Greek goddess who was the 'good sister' of Nemesis.

EVIDENCE FOR NEMESIS' EXISTENCE

Although yet to be proven, there are signs pointing towards a twin star

COMPANION STARS DO EXIST

We know that many stars have a companion, but in 2017 it was suggested that pretty much every star like the Sun had one. Indeed, Sarah Sadavoy and Steven Stahler argued the case for our Sun's companion, but said the partner separated shortly after formation.

OTHER BINARIES HAVE SIMILAR EFFECTS

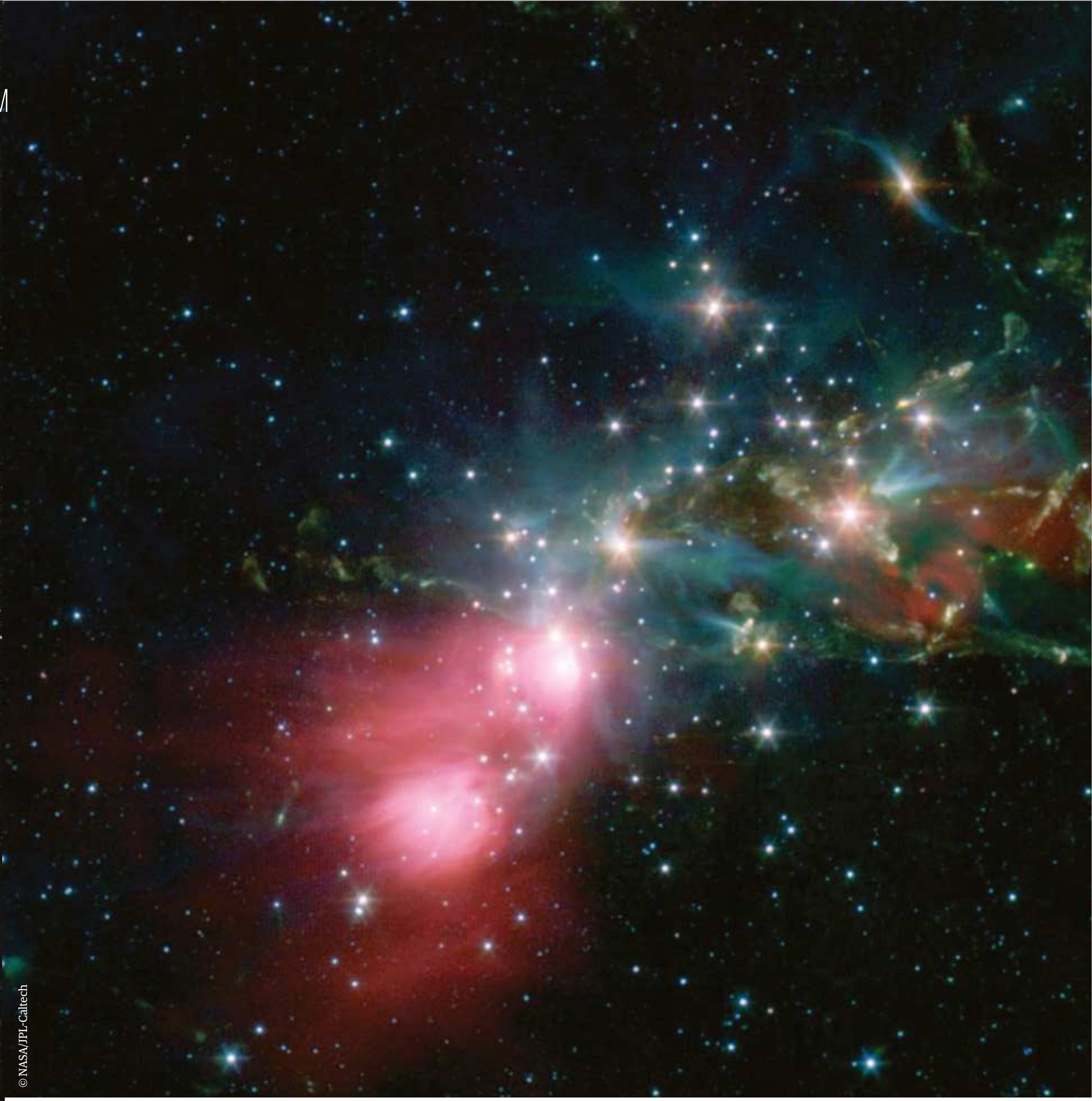
In 2006, debris discs around two nearby stars were seen by researchers at the University of California, Berkeley, to resemble the Kuiper Belt with a sharp outer edge. It was proposed that a companion star causes this effect.

THE PRESENCE OF SEDNA

A trans-Neptunian object called Sedna has an unusual elliptical orbit around the Sun, and some say this is due to the influence of a potential binary companion. Sedna, with an orbit of 12,000 years, has been heralded as strong proof of a companion star for the Sun.

IT IS JUST TOO FAR AWAY

It's not evidence per se, but the Sun's companion star – at least following Sadavoy and Stahler's model – could now be thousands of light years away, which accounts for why it has never been seen.



"WE THINK THE SUN'S COMPANION DRIFTED AWAY BILLIONS OF YEARS AGO, WITHIN A MILLION YEARS AFTER THE SUN AND ITS COMPANION FORMED" STEVEN STAHLER

when Lucie Jílková of Leiden Observatory in the Netherlands suggested a passing star flung it into interstellar space when the Sun was very young.

Yet today Brown tells us that he's not too certain about such theories. "Sedna's orbit is most likely caused by Planet Nine," he says, referencing a hypothetical planet in the outer region of the Solar System. In that sense, he believes there simply is no Nemesis.

"Very sensitive searches have failed to discover it," he affirms. "And, more importantly, the idea that there was periodic extinction appears to have been a misinterpretation of the data. So I think there is both no Nemesis and no need to explain the data! I'm also pretty sure that Nemesis hasn't been a viable hypothesis for more than a decade."

Even so, the case remains open because the hypothesis of a companion star has actually moved on in recent years. While the original theory of Nemesis is perhaps not as strong today as it previously has been, there remains a firm belief in some quarters that the Sun was not born alone.

In 2017, Sarah Sadavoy and Steven Stahler carried out a study called 'Embedded Binaries and their Dense Cores'. Sadavoy, then a radio astronomer from the Max Planck Institute for Astronomy and Stahler, a theoretical physicist from the University of California, Berkeley, discussed how radio surveys of a giant molecular cloud filled with recently formed stars in the constellation Perseus led them to theorise that all Sun-like stars are likely to have been born with companions.

"I do believe this," Stahler tells **All About Space**. "The fact was already known for massive stars, and in 2017 Sarah Sadavoy and I provided strong evidence that low-mass stars like the Sun also tend to form with a companion." In the case of the Sun, this happened 4.5 billion years ago and meant it was born along the same lines as our nearest neighbour, Alpha Centauri, which is a triplet system.

"I believe there was probably a Nemesis a long time ago," he says, explaining that the mathematical

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Left:
Sarah Sadavoy and Steven Stahler say low-mass stars are always born with a companion but are likely to split, like the Sun

Right:
The cold dwarf planet Sedna is said reside at the outer edges of the known Solar System from where the Sun appears as an extremely bright star

Below:
It was thought that the Sun's hypothesised twin, Nemesis, caused disruption to icy rocks in the Oort Cloud, causing chaos on Earth

model explaining the Perseus observations would only be possible if Sun-like stars are born with a companion. "We showed that probably all stars like ours form with companions," he tells us, "but that most, including the Sun, then lose those companions within the next million years."

The work built on that of Pavel Kroupa of the University of Bonn, whose computer simulations in 2011 led him to conclude that all stars are born as binaries. "Stars generally do not form in isolation but are born together in groups within clouds of gas and dust or nebulae," Kroupa wrote. "These stellar labour rooms produce binary star systems, which means that virtually all newborn stars have a companion. Most of these groups of stars disperse quickly so that their members become part of the galaxy."

In the case of Nemesis - or at least in the case of Sadavoy and Stahler's version of a companion Sun - the Sun's sibling escaped and mingled with other stars in the Milky Way. Stahler says he doesn't subscribe to the view that it then caused strong comet activity in the Oort Cloud. "20 years ago astronomers thought so, but few people believe that now," he affirms. Neither does he believe that the Sun has any influence over its companion.

"Muller's theory is different," he explains. "He postulated that the Sun currently has a companion on an eccentric orbit but, despite a lot of effort, this companion has never been found." Stahler is unsurprised that a form of Nemesis has never been discovered, though. "We think the Sun's companion drifted away billions of years ago, within a million years after the Sun and its companion formed," he says. "It could now be on the other side of the galaxy."

Such findings have wide implications, and they go to the heart of the origins of galaxies. In the case of Perseus there were 45 single-star systems, yet all but five of the 55 young stars in 24 multiple-star systems were binary. More than that, all of the widely separated binary systems - which are those with stars separated by more than 500 AU - were young systems.

"Our finding that most stars are born with companions is interesting for those of us who think about stellar birth," Stahler says. "Apparently our Sun, and also the Solar System, was born from an elongated gas cloud that formed another star - and perhaps another planetary system - as well. We see lots of such clouds, so studying them will tell us the conditions under which we formed."

It's the most compelling evidence that our Sun was once part of a binary star system, but the emphasis on 'once' cannot be stressed enough. As for the figure of 26 million years, well, that too is in doubt, with Adrian Melott and Richard Bambach having argued in their paper, *Nemesis Reconsidered*, that "the orbit of a distant companion to the Sun is expected to be perturbed by the galactic tidal field and encounters with passing stars, which will induce variation in the period".

What all of this means is that the Sun's potential twin is off the hook with regards to it being a mass-murderer, but there is great weight to Muller's assertion that the Sun was born with a companion. Unfortunately it'll be so far away now that we're unlikely to ever see it, it's history perhaps forever keeping us in the dark.

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